Chapter 5
Physico-chemical Characterization and Development of Hemp Aggregates for Highly Insulating Construction Building Materials

Yunhong Jiang, Atif Hussain, Davoud M. Heidari, Michael Lawrence, and Martin Ansell

Abstract The natural hemp aggregates and their bio-composite panels which have been developed for sustainable construction with low thermal conductivity and high hygrothermal efficiency. The combination of the hemp aggregates with natural matrix materials results in exceptionally low thermal conductivity and high hygrothermal efficiency compared to conventional materials of construction as a result of their microporosity and breathability. In addition, the developed bio-based composites with nanotechnology improve resistance to liquid water and protect the hemp shiv from biodegradation without impacting the natural ability of the shiv to buffer moisture vapor.

The chapter assesses the physical characteristics of hemp aggregates in terms of their density, microstructure and porosity. Hemp-concrete and novel Hemp-organic composite have been studied and compared. Measurements of the thermal conductivity of hemp-composite panels are described which confirm their highly insulating properties. Hygroscopic testing demonstrates their effectiveness in absorbing and releasing moisture. The thermal and hygroscopic performance of hemp-composite panels in test cells is reported together with their application in construction. The life cycle assessment of hempcrete and hemp organic composite were performed. This chapter is part of the output of the ISOBIO programme supported by the European Union Horizon 2020 program, within the 'Materials for Building Envelopes' call for Energy Efficient Buildings.

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Keywords Hemp aggregates · Hemp-composite · Hygrothermal properties · Nanotechnology · Life cycle assessment

Abbreviations

AV	Average value
CO_2-eq	Carbon dioxide equivalent
CoV	Coefficient of variation
GHG	Greenhouse gases
GWP	Global warming potential
HDTMS	Hexadecyltrimethoxysilane
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MBV	Moisture buffer value
MIP	Mercury intrusion porosimetry
Ơ	Standard deviation
RH	Relative humidity
SEM	Scanning electron microscopy
TEOS	Tetraethyl orthosilicate

5.1 Introduction

Using environmental-friendly and sustainable industrial bio-based plant aggregates as raw materials for building insulation and construction is a new approach to address climate change and reduction in carbon dioxide emission. The advantages of bio-based plant materials include a renewable supply chain and significantly reduced carbon footprint through the photosynthetic carbon stored within plant-based materials. The bio-based insulation materials, such as natural fibre batts, offer many benefits in comparison with more established mineral and oil-based alternatives, such as mineral wool and polyurethane rigid form (Binici et al. 2016; Lopez Hurtado et al. 2016). A major advantage of bio-based insulation materials is their ability to form a breathable wall by readily absorbing and desorbing moisture in response to changes in relative humidity (RH) and vapour pressure gradients in the surrounding environment, acting as a hygric buffer, reducing the energy requirements of air conditioning and increasing the comfort of the occupants in the building (Collet et al. 2013; Rahim et al. 2015; Mazhoud et al. 2016). The most commonly available bio-based insulation materials include wood fibre/wool, cellulose, hemp fibre, flax fibre and sheep's wool et al. Their properties have been fully studied by researchers and industrial partners. Table 5.1 shows the typical density and thermal conductivity of the common bio-based

Table 5.1 Properties of the common bio-based insulation materials on the market

Material	Typical thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Typical density ($kg\ m^{-3}$)	Typically embodied energy cradle to the gate ($MJ\ kg^{-1}$)	Manufacturer
Wood fibre	0.038–0.050	160–240	17	Biofib Insulation/FiBRA Natur/Isonat/Steico/Pavatex
Wood wool	0.038–0.040	50	10.8	Biofib Insulation/FiBRA Natur/Isonat/Steico/Pavatex
Paper (cellulose)	0.035–0.040	32	4.9–16.64	Homatherm/Isonat/Fiberlite Technologies/Warmcell
Hemp fibre	0.038–0.040	40	10.5–33	Thermafleece/ Blackmountain/NaturePro/ Pavatex/Hemp Flex/ Lenofon/Nord Tex
Sheep's wool	0.038–0.040	25	12–36.8	Thermafleece/ Blackmountain/NaturePro/ Pavatex/Hemp Flex/ Lenofon/Nord Tex
Flax fibre	0.038–0.040	30–35	11–39.5	Thermafleece/ Blackmountain/NaturePro/ Pavatex/Hemp Flex/ Lenofon/Nord Tex
Cork	0.038–0.070	105–120	26	Amorim/Jelinekcorkgroup/ EnviroNomix/Thermacork/ Agepan
Straw bale	0.052–0.080	100–130	0.24	Stramit/ModCell/Baustron

insulation product on the market. The thermal conductivity of these bio-based products ranges from 0.35 $W\ m^{-1}\ k^{-1}$ to 0.08 $W\ m^{-1}\ k^{-1}$, which are generally more thermally conductive than synthetic materials which tend to range between 0.023 $W\ m^{-1}\ k^{-1}$ (polyurethane) and 0.044 $W\ m^{-1}\ k^{-1}$ (mineral fibre) (Lawrence et al. 2013). Oil derived insulation has the highest embodied the energy of between 95 and 108 $MJ\ kg^{-1}$, and mineral insulation is between 15.7 and 53 $MJ\ kg^{-1}$, while bio-based natural insulation has the lowest embodied energy from cradle to gate between 0.24 and 39.5 $MJ\ kg^{-1}$, as shown in Table 5.1 (Lee and Yeom 2014; Miller and Ip 2013).

However, the bio-based plant aggregates (shiv), which come from the by-product of the stalks of plants, have not to be fully studied as building insulation materials. Bio-based plant aggregates, come from same plant stalk of fibre/seed, are very porous with a low density and have similar hygrothermal properties compared to the product of fibre. Tran et al. (2010) reported the hierarchical cell wall structure of bio-based plant aggregates resulted in good air tightness and minimal thermal bridging of the building. They have huge potential to be used in mainstream building insulation industrial. Recently, several European projects such as ISOBIO, ECO-SEE and HEMPSEC start to create the prefabricate panels using bio-based plant aggregates with an insulation purpose. Among these bio-based plant aggregates, the hemp shiv composite is probably the most widely used and studied in building industry in

Europe. They usually mixed with a lime-based binder to form a hemp concrete, which is known as hemp-lime (Latif et al. 2014; Rahim et al. 2015, 2016).

Collet et al. (2013) compared the hygric behaviour of three hemp concretes, which are a precast compacted hemp concrete, a sprayed hemp concrete and a moulded hemp concrete with fibred hemp shiv. They have a similar hemp/binder mass ratio of 0.5, apparent density between 430 and 460 kg.m^{-3} and a total porosity ranging between 72 and 79%. The results showed the hemp concretes are excellent hygric regulators and the total porosity and manufacturing method have a slight effect on the hygric performance of hemp concrete.

Rahim et al. (2015) reported the excellent hygric properties of hemp-lime concrete and flax-lime concrete according to the classification proposed by the Nordtest project. The density of hemp-lime concrete is around 478 $\pm$ 7 kg.m^{-3}, whereas the density of flax-lime concrete is about 598 $\pm$ 4 kg.m^{-3}. The porosities of hemp-lime concrete and flax-lime concrete are 76.4 $\pm$ 0.1% and 70.6 $\pm$ 0.3%, respectively. Rahim et al. (2016) also reported the hygric properties of rape straw concrete and hemp concrete. They have a similar density between 478 and 487 kg.m^{-3} and total porosity between 75.1 and 76.4%. The moisture buffer value (MBV) for hemp concrete and rape straw concrete are 2.02 and 2.59 g m^{-2}% RH^{-1}, respectively. Mazhoud et al. (2016) studied the hygric and thermal properties of hemp-lime plasters with densities between 723–881 kg.m^{-3} and total porosities ranging from 65.9 to 72%. The MBV of hemp-lime plaster is between 1.23 and 1.64 g/m^{-2} RH %$^{-1}$, which is lower than value above due to the lower hemp to binder ratio in hemp lime plaster than in hemp concrete. The thermal conductivity of hemp-lime plasters is about 0.2 W m^{-1} K^{-1}. They also claimed that the particle size of hemp shiv has a slight impact on the hygric and thermal properties of hemp-lime plaster.

Much of the existing characterization data for natural bio-based aggregate composites relates to their physical (bulk density and complex cell wall structure) and chemical properties (ratio of cellulose, hemicellulose and lignin), pore structure, porosity and pore connectivity (Bismarck et al. 2002; Chundawat et al. 2011; Zhang et al. 2012; Lawrence and Jiang 2017). However, a few studies have explored their scientific characteristics from the benchmark point of bio-based raw aggregates as building insulation materials due to no standardized methods for characterizing such materials. Jiang et al. (2018) studied the cell wall structure, pore size distribution and absolute density of hemp shiv using different approaches. They found the mercury intrusion porosimetry (MIP), which covers a wide range of pore size between 0.003 μm and 100 μm, is a solid method to measure the porosity and absolute density for hemp shiv. Laborel-Preneron et al. (2018) characterised the density, thermal conductivity and sorption-desorption properties of barley straw, hemp shiv and corn cob. They reported that the thermal conductivities are 0.044, 0.051 and 0.096 W m^{-1} K^{-1} respectively for straw (density: 57 kg m^{-3}), hemp shiv (density: 153 kg m^{-3}) and corn cob (density: 497 kg m^{-3}). The RILEM BBM Technical Committee, which set up in 2011, starts to work on the standard protocols for bio-based plant aggregates characterisation (Amziane et al. 2017). The characterisation of the hygrothermal properties of bio-based plant aggregates is still at an early stage.

In this chapter, we fully scientific characterization of hygrothermal and moisture buffer value of the natural hemp aggregates and their bio-composite panels which have been developed for sustainable construction with low thermal conductivity and high hygrothermal efficiency. The bulk density, absolute density, porosity and particle size distribution of these industrial bio-based plant aggregates are analysed using RILEM recommendation methods and MIP method. The microstructure was comparably studied among these aggregates using scanning electronic microscopy (SEM). The thermal and hygroscopic performance of hemp-composite panels in test cells is reported together with their application in construction. The life cycle assessment of hempcrete and hemp organic composite were performed. These data will provide the benchmark data and give a guidance to develop the novel bio-based plant aggregates insulation composites for use in the building insulation industry.

5.2 Characterization of Hemp Aggregates

The SEM microstructures of industrial hemp aggregates are shown in Fig. 5.1. The SEM images showed that the samples have a porous microstructures. It clearly showed the three zones of pith, xylem layer and epidermis from the interior to the exterior of the hemp stem. At higher magnification, the radial arrangement of cells in the xylem layer is visible. A closer view of the pith reveals the foam-like closed cell structure with some voids at the interfaces between cells. The average diameter of parenchyma cells are approximately 5–20 μm. The xylem contains a range of cell diameters the larger cells being termed vessels. The vessels exhibit little variation in size and no clear pore arrangement, which is a diffuse-porous distribution. The vessels are approximately 50 to 100 μm in diameter and are surrounded by relatively thick fibre cells. Thick-walled fibres are located between the vessels with a diameter from 1 μm to 2 μm.

The bulk density and skeleton density of bio-based plant aggregates are given in Table 5.2. The standard deviation between the five measurements of bulk density is very low for all hemp shiv. The accuracy of the measurement was calculated from the characteristics of the balance and from the accuracy of the level, estimated about 0.5 mm. This accuracy is better than 1%. For each material, the measurement is repeated five times. The protocol was based on that developed by the RILEM Technical Committee 236-BBM. Generally, the bulk density of aggregate decreases when the size of aggregate increases. For hemp shiv, the bulk density at dry state ranges from 88 to 104 kg m^{-3}. The skeleton density is similar for all sizes of hemp shiv. The skeleton densities of hemp shiv are close with average values of 1452 kg m^{-3}.

The porosity of the bulk material, including inter-particles and intra-particles porosity, is high. For all the tested hemp shiv, it is higher than 90%. A slight increase of porosity with aggregate size can be noticed, probably as a result of larger voids being created between large particles. The properties of hemp shiv are not only affected by the total pore volume and porosity, but also affected by the pore size

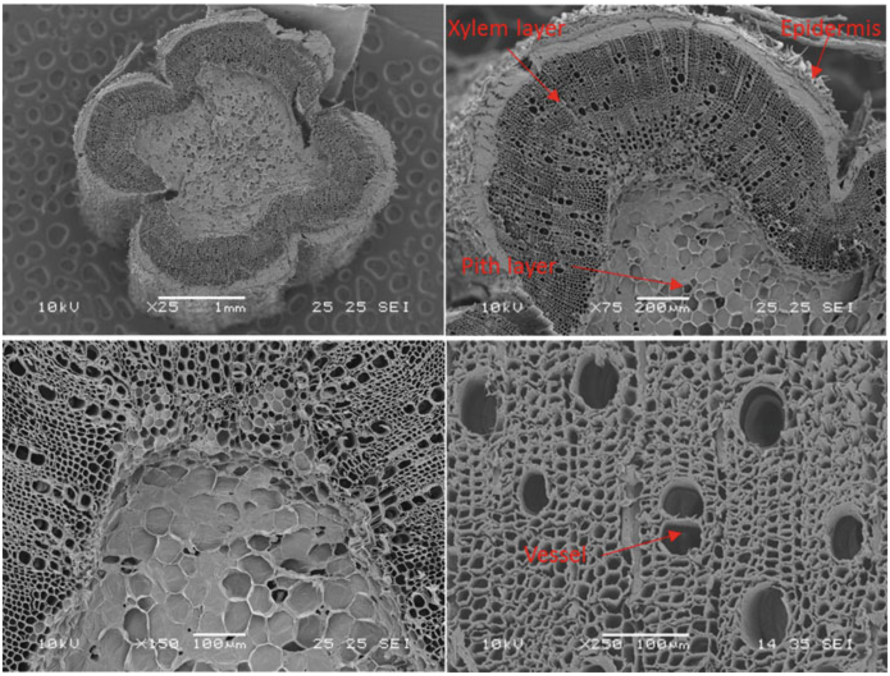

Fig. 5.1 Scanning electron microscopy micrographs of hemp shiv. The industrial bio-based plant aggregates used in this study was sourced and harvested in North West France. They were produced by a mechanical de-fibring processing removing the fibre, chopping, grading and de-dusting and supplied by the CAVAC cooperative (France). The microstructure of the bio-based plant aggregates was characterised using a scanning electron microscope (JEOL SEM-6480LV, Tokyo, Japan). All images were taken at an accelerating voltage of 10 kV. The sample surfaces were coated with a thin layer of gold using an HHV500 sputter coater (Crawley, UK) to provide electrical conductivity sending electrons to earth

Table 5.2 Bulk density and skeletal density of hemp shiv at dry state; The particle size of hemp shiv are calibrated with different sieving grids using a grader such as G7, G8, G12 and G14

Name		Hemp Shiv			
Grade		G7	G8	G12	G14
Bulk density (kg m^{-3})	Av.	104.01	96.65	90.72	87.89
	σ	1.44	0.62	1.48	2.13
	c. Var.	1.36	0.72	1.56	2.35
Skeleton density (kg m^{-3})	Av.	1452			
	σ	83			
	c. Var.	6.11%			

Av.: Average value; σ: Standard deviation; c. Var.: Coefficient of variation

distribution and pore structure. Figure 5.2 display the relationship between the pore diameter and the mercury intrusion volume and the log differential mercury intrusion volume as a function of the pore diameter and pore size distribution curves of hemp shiv determined by mercury intrusion porosimetry. Because of technical restrictions

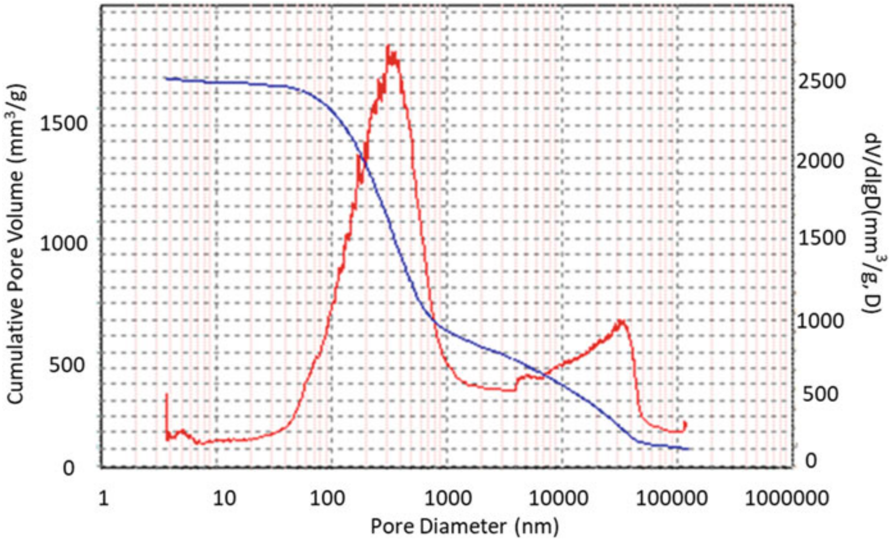

Fig. 5.2 Pore size distribution curves of hemp shiv determined by mercury intrusion porosimetry (PASCAL, Thermo Scientific). Blue line is cumulative pore volume and red line is dV/dlogD. The pore size distribution was presented in the form of cumulative pore volume and logarithmically differential pore volume curves as a function of pore radius. Full details of the methods and measurement process used are as reported by Jiang et al. (2018) (Color figure online)

the measurement of the large tracheids with 100 μm is excluded. Those pores are on the one hand important openings for impregnation but on the other hand easily accessible already without or with low applied pressures. The differential PSD curves clearly show that the aggregates have similar PSDs with representative peaks at pore radii around 0.02–100 μm. However, the magnitude and shape of the peaks differed among different shiv. The vast majority of the pores seen were in the range of 0.1–10 μm. For hemp shiv, they have a similar bi-modal peaks. The results show good agreement with the results of SEM.

Figure 5.3 showed the thermal conductivity of hemp shiv aggregates at dry state using heat flow meter and CT meter methods. The results also compared with the thermal conductivity of their other forms, including fibre and fine powder and plus corn cob. The results measured by the FOX600 are represented by the blue colour and the grey colour represents the results of CT meter. Generally speaking, both methods show relatively similar thermal conductivity on all the bio-aggregates. The thermal conductivity of bio-aggregates ranges from 0.04 W m^{-1} K^{-1} to 0.06 W m^{-1} K^{-1}, except for corn cob, which shows a significantly higher thermal conductivity of 0.08 W m^{-1} K^{-1}. For all the shiv samples, wheat straw G7 and G8 show the lowest thermal conductivity, which is around 0.04 W m^{-1} K^{-1}. Rape shiv shows a slightly lower thermal conductivity than the thermal conductivity of hemp and flax. There are similar results for the thermal conductivity of hemp powder and

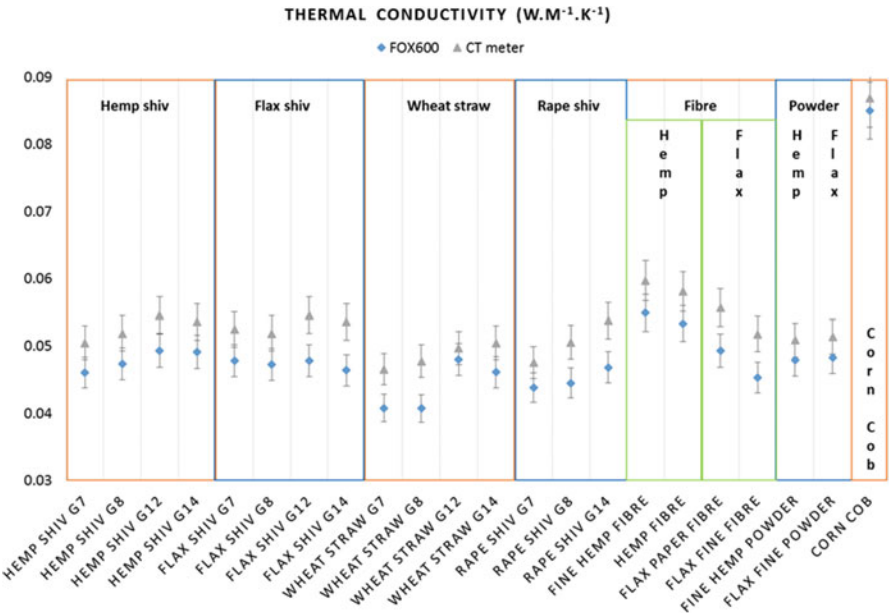

Fig. 5.3 Thermal conductivity of bio-aggregates measured by Fox 600 and CT meter. The industrial bio-based plant aggregates used in this study was sourced and harvested in North West France. They were produced by a mechanical de-fibring processing removing the fibre, chopping, grading and de-dusting and supplied by the CAVAC cooperative (France). The selected bio-based plant aggregates are hemp shiv (grade 7, 8. 12 and 14), flax shiv (grade 7, 8, 12 and 14), rape shiv (grade 7, 8 and 14) and wheat straw (grade 7, 8, 12 and 14)

flax powder. There is no significant difference in thermal conductivity of shiv with different particle sizes, except wheat straw G12 and G14. Wheat straw G12 and G14 show a significantly higher thermal conductivity at lower density due to the additional impact of convection currents. Compared to hemp shiv, both hemp fibre and fine fibre show a slightly higher thermal conductivity. In addition, hemp powder shows a similar thermal conductivity to hemp shiv. It can be concluded that the particle size has little effect on the thermal conductivity of bio-aggregates.

5.3 Binders and Formulation

The hemp organic composites described here was prepared by using a bio-based polysaccharide binder as a matrix binding together the hemp shiv. The bio-based binder was formulated using a starch derivative and a crosslinking agent. Two sets of hemp organic composites were developed for this study consisting of, (i) Untreated hemp composite: raw hemp shiv aggregates and bio-based binder; and (ii) Treated hemp composite: modified hemp shiv aggregates using a hydrophobic pre-treatment and bio-based binder.

The hemp shiv aggregates were pre-treated with a silica-based coating prior to composite preparation for improving the water resistance of the composites. For preparation of the treatment solution, the sol-gel process was followed. 1 M of tetraethyl orthosilicate (TEOS) was added as the silica component to a mixture of 4 M distilled water, 4 M of absolute ethanol and 0.005 M of nitric acid. 0.015 M of hexadecyltrimethoxysilane (HDTMS) was added to the above mixture as the hydrophobic agent. The sol was vigorously stirred for 2 h at 40 °C and atmospheric pressure. The sols were then aged for 96 h in closed container at room temperature before the treatment process. The hemp shiv aggregates were dipped in the sol for 10 min, transferred to an open tray and then dried at room temperature for 1 h. Finally, the hemp shiv aggregates were placed in an oven at 80 °C for 1 h.

Mixing of the constituent materials, hemp shiv aggregates and the bio-based binder, was performed manually to achieve a uniform mixture. The mass of the constituent materials was precalculated to achieve targeted final composite densities (200 kg m^{-3} for the untreated composite and 240 kg m^{-3} for the treated composite). The weight ratio for hemp shiv: binder was 9:1 for both untreated and treated composites. The difference in the final densities of both composites was mainly due to the treatment process depositing silica on the surface of the treated hemp shiv aggregates.

For preparation of the composites, the mixture of the constituent materials was placed into a steel mold of desired dimension and compacted at 0.5 MPa using a hot press (PressMasters 40 T GEM series). The upper and lower plates were then heated to 180 °C and the temperature was maintained for 1 h. The specimens were demolded after cooling down to room temperature and then transferred to a conditioning room at 19 °C and 50% relative humidity.

5.4 Characterisation of Composites

5.4.1 Moisture Buffering

The moisture buffering property of a material corresponds to its ability to absorb and release moisture in response to varying relative humidity levels in internal spaces. This property can have a positive impact on the indoor comfort levels and reduce the energy consumption required for air conditioning (Tran et al. 2010). The moisture buffering performance of construction materials depends on the exposure area, vapour permeability, ventilation rate and surface pre-treatments (Latif et al. 2015).

The Nordtest protocol is the most common method to estimate the moisture buffer value (MBV) of a material (Rode et al. 2005). The kinetics of mass change for the organic hemp composite panels developed under the ISOBIO project is presented in Fig. 5.4. The mass change was calculated per m^2 exposed surface of the samples and plotted against time.

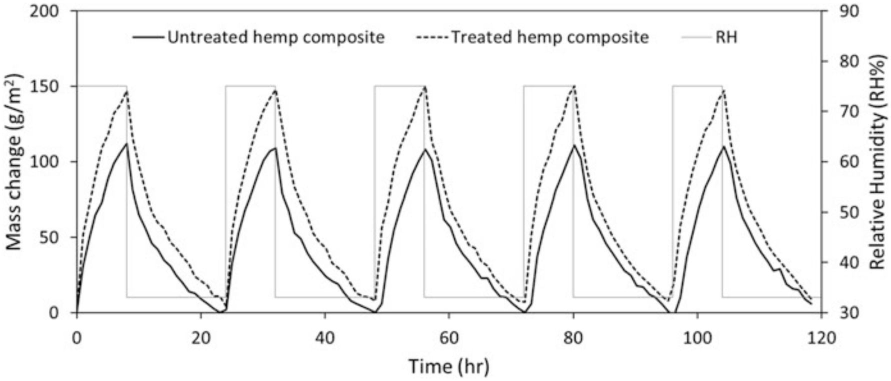

Fig. 5.4 Mass change of ISOBIO hemp shiv composite panels exposed to varying relative humidity at 23 °C

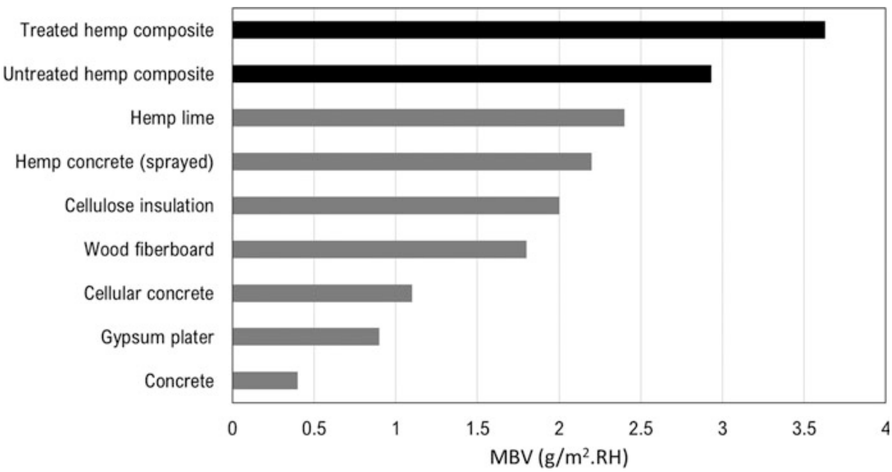

Fig. 5.5 Moisture buffer value of general building materials vs the hemp organic composites (Rode et al. 2005; Collet and Pretot 2012)

The MBV of the usual building materials reported in literature is shown in Fig. 5.5 and compared with the MBV obtained for the organic hemp composites. The materials can be rated according to their MBV as: negligible (MBV $\leq$ 0.2 g m^{-2} RH), limited (MBV 0.2–0.5 g/m^2RH), moderate (MBV 0.5–1.0 g/m^2RH), good (MBV 1.0–2.0 g m^{-2} RH) or excellent (MBV $\geq$ 2.0 g m^{-2} RH). From Fig. 5.5, it can be seen that the prepared hemp organic composites show excellent moisture buffering capacity. The MBV of the both untreated and treated hemp composites is higher than hemp concrete reported in literature (1.75–2.15 g m^{-2} RH) (Tran Le et al. 2010; Collet and Pretot 2012; Dubois et al. 2014). The high hemp shiv binder ratio in these composites result in lower density and thereby enhancing their vapour permeability.

5.4.2 Vapour Permeability

The vapour permeability of a porous material can be expressed by its ability to transfer moisture through a vapour pressure gradient. Moisture transfer takes places in three stages: diffusion such as self-collision of water molecules, effusion including collision of water molecules with the pore walls and liquid transfer associated with capillary condensation (Collet et al. 2013).

Using a vapour permeable wall and maintaining indoor relative humidity levels between 40 and 60% can have a positive impact on wellbeing of residents, controlling respiratory problems and reducing allergies (Maskell et al. 2018). When bio-based materials are used as part of a vapour permeable wall, moisture can penetrate through the fabric of this wall. The risk of moisture build-up is considerably reduced which is expected to reduce bacterial growth, thereby improving the overall indoor air quality (Osanyintola and Simonson 2006; Zhang et al. 2012).

The water vapour permeability and the diffusion resistance factor of thermal insulation materials can be measured using the British Standard BS EN 12086 (BS EN 12086, 2013) under isothermal conditions (23 °C) and at two sets of relative humidity: dry cup and wet cup. The kinetics of mass change of the hemp organic composites presented in Fig. 5.6.

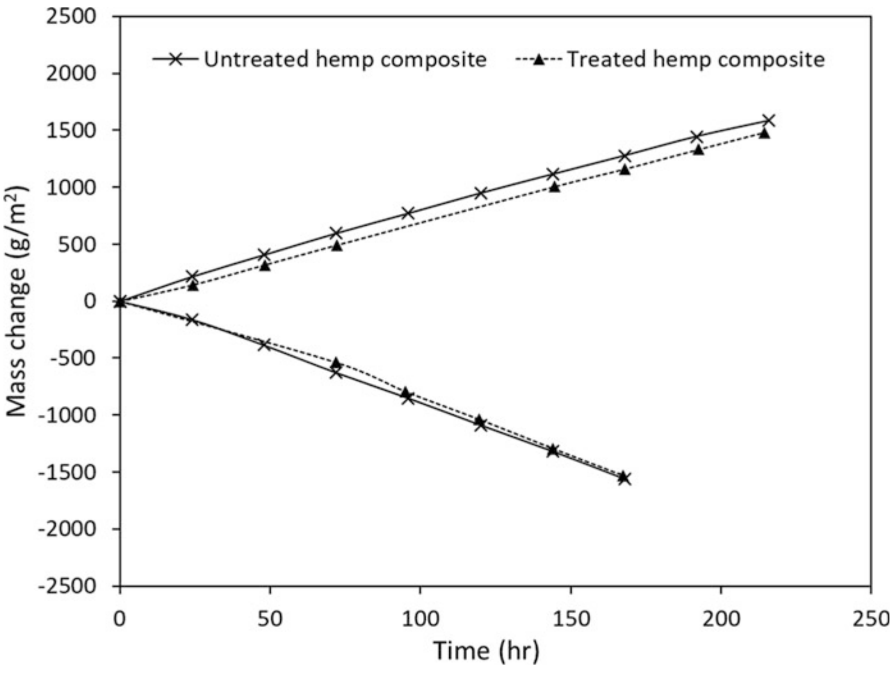

Fig. 5.6 Mass change of the hemp organic composites during the vapour permeability test

Table 5.3 Vapour permeability results of the hemp organic composites

Parameters	Untreated hemp composite		Treated hemp composite	
	Dry cup	Wet cup	Dry cup	Wet cup
Water vapour transmission rate, g (mg h^{-1})	6343.75	9833.33	7224.33	9605.63
Water vapour permeance, W (mg m^{-2} h Pa)	4.72	8.13	5.37	7.94
Water vapour resistance, Z (m^2 h Pa mg^{-1})	0.21	0.12	0.18	0.13
Water vapour permeability δ (mg m^{-1} h Pa)	0.09	0.16	0.11	0.16
Water vapour resistance factor μ	7.54	4.37	6.62	4.48

Table 5.4 Thermal conductivity data of the hemp organic composite panels

Parameter	Untreated hemp composite	Treated hemp composite
Thermal conductivity (W m^{-1} K)	0.053	0.057
Thermal diffusivity (10^{-6}) (m^2 s^{-1})	0.35	0.30
Specific heat capacity (J kg^{-1}·K)	763.20	782.71
Bulk density (kg m^{-3})	200.0	240.0
Volumetric heat capacity (10^6) (J m^{-3} k)	0.15	0.18

The composites show promising results as seen in Table 5.3, behaving as a good vapour permeable material. It can be seen from the results that hydrophobic treatment of hemp shiv did not affect the vapour permeability of the material. Bio-based aggregates such as hemp shiv have very high porosity and as a result they have very low water vapour resistance. On the other hand, solid concrete has a very high water vapour diffusion resistance factor at about 130 while for hemp concrete it ranges between 5 and 12 (Walker and Pavía 2014).

5.4.3 *Thermal Conductivity*

The thermal conductivity of the hemp organic composite panels was measured from transient method using a hand-held measuring instrument ISOMET 2114 at 20 °C. The results are reported in Table 5.4. In general, bio-based materials are light in weight and have low thermal conductivity making them good insulation materials. However, the thermal conductivity of the bio-based composite is also influenced by other factors such as aggregate, binder, aggregate to binder ratio and water content. The density can be affected by the formulation, binder content and production method thereby influencing the thermal conductivity as well (Collet and Pretot 2014; Elfordy et al. 2008). Various studies have showed that as the aggregate content is increased, the thermal conductivity decreases for the composite. This is due to the decrease in density of the composite as usually the aggregate has lower density when compared to the binder. Higher aggregate content increases the overall porosity of the composite (Al Rim et al. 1999).

Table 5.5 Water absorption measurements of the hemp organic composite panels

Sample	Water absorption (kg m^{-2})	Water absorption (%)
Untreated hemp composite	22.11 ± 0.7	221.10 ± 1.3
Treated hemp composite	11.04 ± 0.6	98.02 ± 3.5

5.4.4 Water Absorption

The short term water absorption of the specimens was determined by the British Standard EN 1609 (BS EN 1609, 2013). The water absorption of the composites was calculated in two ways: (i) as change in mass over exposed surface area (WA) using Eq. (5.1) where *WA* is the water absorption (kg/m^2), m_0 is the initial mass of the test specimen (kg), m_{24} is the mass of the test specimen after partial immersion for 24 h (kg), A_p is the bottom surface area of the test specimen (m^2); (ii) as percentage of absorption with respect to initial mass (WA%) using Eq. (5.2) where *WA%* is the water absorption percentage.

$$WA = \frac{m_{24} - m_0}{A_p} \tag{5.1}$$

$$WA\% = \frac{m_{24} - m_0}{m_0} * 100 \tag{5.2}$$

The water absorption results are presented in Table 5.5. The untreated hemp composite shows higher values for WA and WA% due to the absence of hydrophobic silica treatment on hemp shiv in the composites. The hydrophobic treatment significantly reduced the WA by 50% and the WA% reduced by 123%.

Hemp shiv possesses a large water absorption capacity due to its internal pore structure and its chemical composition. The low bulk density of hemp shiv aggregates is due to their high porosity (Jiang et al. 2018) which can trap huge amounts of water. Moreover, the presence of high number of hydroxyl groups (Kidalova et al. 2015) in its structure adds to the retention of water within the bulk of hemp shiv aggregates. High sensitivity to moisture can be responsible for colonial fungal growth leading to cell wall degradation and affecting the durability of the material (Marceau et al. 2017). High water absorption capacity can also affect the manufacturing quality of the final product if it encounters water or is exposed to humid surroundings. The silica treatment used in this research reduced the hydrophilicity of hemp shiv as seen with the water absorption tests making them water resistant and less susceptible to degradation.

5.5 Performance of Panels in the Construction

5.5.1 *Hemp Lime Structures*

The use of hemp shiv as a bio-aggregate began in France in 1986 when Charles Rasetti, tasked with restoring a medieval timber framed building in Nogent-sur-Seine, made use of chopped hemp stalk – the waste from the manufacture of hemp fibre based paper – mixed with a lime binder as infill in place of wattle and daub. This was found to be highly effective and it use soon spread to the construction of new buildings. Yves Kühn developed the 'Canosmose' system of construction, based on hemp-lime, and by the mid 1990s a hemp specific binder (Tradical®) had been developed by Strasservil to feed the burgeoning demand. In 1998 the professional association 'Construire en Chanvre' was founded, and in 2007 they published 'Règles Professionelles' giving formal guidance on how to build with hemp-lime. By the start of the twenty-first century, hemp-lime construction had been adopted in other European countries as well as in North America, South Africa, Australia and New Zealand. It is now widely used across the world, albeit by enthusiasts rather than main-stream construction companies, but large-scale hemp-lime construction systems are being developed in both France and Australia and expected to make an impact by 2025. In the UK a number of housing developments have been concluded using hemp-lime (Fig. 5.7). Much of the validation for the use of hemp-lime has been based on laboratory based tests rather than measurements taken in actual buildings, from which mainly anecdotal evidence is available. Notable exceptions include an early study done in the UK in 2002 (BRE 2002), which did not identify any particular benefits, and a recent study (Moujalled et al. 2018), which validated a theoretical model over a 4 year period using data from a domestic house. This study demonstrated that hemp-lime is a good hygrothermal regulator, managing internal humidity effectively and showing good thermal inertia.

Fig. 5.7 Examples of housing developments in the United Kingdom

5.5.2 Hemp Organic Composite

The hemp organic composite which is the subject of this chapter was developed as part of the EU funded ISOBIO project and three ISOBIO wall systems and four reference walls were monitored at test facilities in the UK and Spain, for the purpose of measuring thermal transmittance using the Heat Flow Meter method to ISO 9869, and comparing results with calculated U-values to ISO 6946. The results show a measured reduction in thermal transmittance of the ISOBIO New-build panel of 65% in the UK and 54% in Spain, in comparison with their respective reference new-build walls (constructed from traditional materials to current standards). Figure 5.8 below shows a comparison of the measured U-value of the ISOBIO New-build panel, compared with the Reference New-build cavity wall. The results show a 65% reduction in thermal transmittance of the ISOBIO panel compared with the New-build cavity wall.

If we consider the ISOBIO New-build panel's moisture buffering performance and impact on internal relative humidity, we can see that the panel offers superior performance compared to the Reference cavity wall. Figure 5.9 below shows the relative humidity in Cell 4 (ISOBIO New-build panel) compared with Cell 1 (Reference New-build cavity wall), during the same period (24/02–14/03). The ISOBIO panel in Cell 4 helps maintain an average RH of 42% (within the optimum comfort

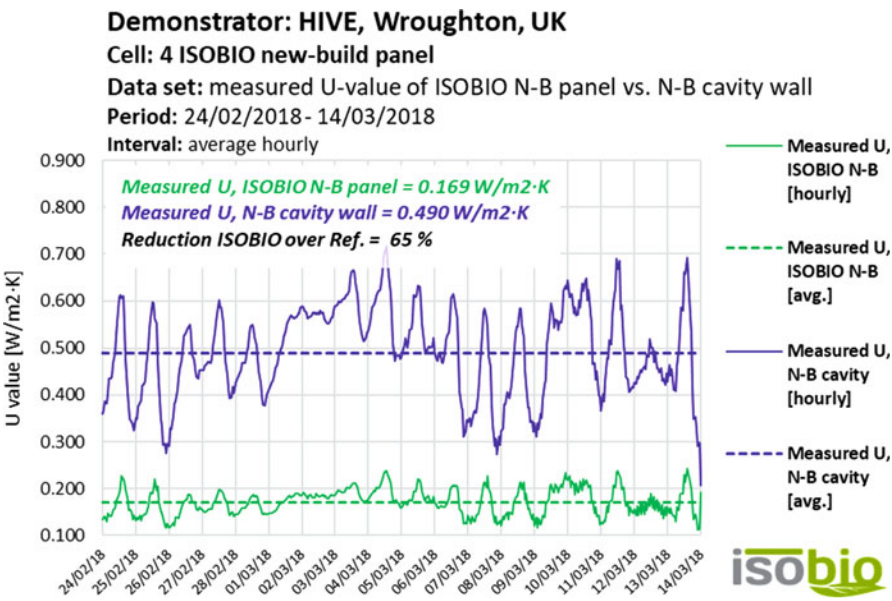

Fig. 5.8 Measured U-value of ISOBIO New-build panel vs. Reference New-build cavity wall, HIVE, United Kingdom

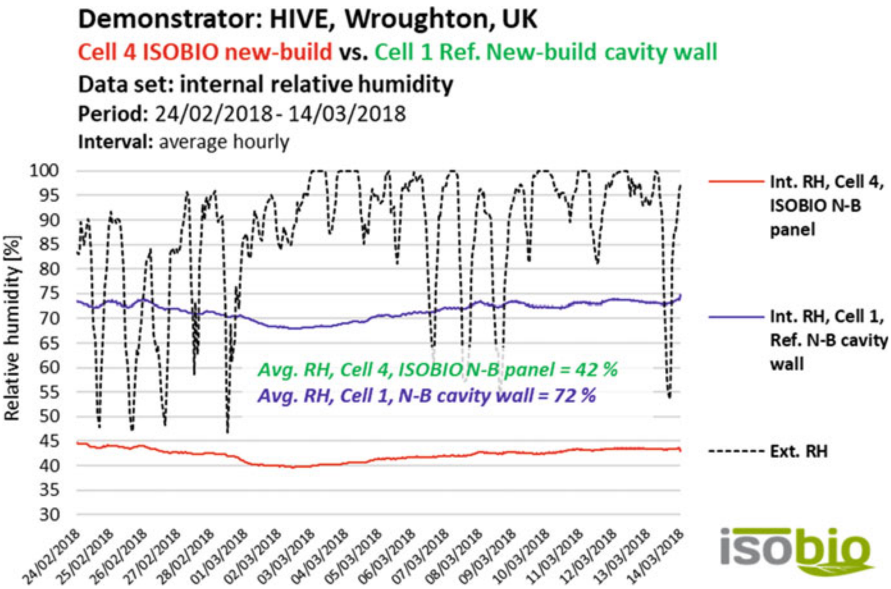

Fig. 5.9 Average internal relative humidity of Cell 1 (ISOBIO New-build panel) vs. internal relative humidity of Cell 1 (Reference New-build cavity wall), HIVE, United Kingdom

range for indoor relative humidity), while in Cell 1, the New-build cavity wall (being vapour impermeable), does not allow water vapour to dissipate, and RH remains at an average of 72%.

The ISOBIO External retrofit system reduced thermal transmittance by 55% (UK) and 71%, (Spain), in comparison with their respective reference walls. The ISOBIO Internal retrofit system reduced thermal transmittance by 77% (UK) and 81% (Spain). The UK monitoring results show that the ISOBIO new-build panel is a high-performance composite wall system, with a very good correlation between calculated and measured values and a near-zero performance gap. The data suggests that bio-based materials, when combined in a structural insulated panel with an air barrier, can provide predictable performance and high thermal resistance, that will reduce heating and cooling energy consumption at building scale.

Monitoring data of the ISOBIO New-build panel during 4 days in August showed an average heat flux of -2.3 W m^{-2}, compared with -7.6 W m^{-2} in the New-build cavity wall, demonstrating that the ISOBIO New-build panel can offer good thermal performance in warm climates and reduced energy consumption from air conditioning. This was confirmed by the calculation of weighted energy savings during the summer period, which showed that the ISOBIO New-build panel generated a 14% saving in cooling energy consumption.

5.6 Life Cycle Assessment of Hemp Shiv Composite

The construction sector is responsible for 40% of materials and energy consumption of the world (Abd Rashid and Yusoff 2015). Concerning the environmental impacts of construction sector such as global warming potential ozone layer depletion, this industry is forced to take in to account new strategies to mitigate its' energy consumption. Whereas in the past the building sector primarily used materials that were local to the construction site with low environmental impact and energy consumption, nowadays the building sector uses global materials with high environmental impact and energy consumption such as concrete, gypsum, steel, aluminum and polyvinyl chloride. Innovative bio-based materials such as hemp shiv are being developed for use in construction, with the goal of being more environmentally friendly during their life cycle. Even though the introduction of innovative bio-based material will reduce the carbon footprint compared with fossil-based materials, it may incur some additional costs such as land use and its related environmental impacts.

Environmental assessment is required to make a strategic decision related to the use of these bio-based materials instead of their fossil-based ones. The growing use of bio-based materials in the construction sector calls for an assessment of their environmental impact. Life Cycle Assessment (LCA) as an environmental assessment technique is used to analyze the environmental impacts of product systems through their life cycle. Some environmental impacts can vary depending on the characteristics of their surroundings, and therefore on the location of the activity. Regionalized LCA is a technique that takes in to account this variability. Previous LCAs has been conducted on a wide range of bio-based materials, including hemp-concrete known as hempcrete (Andrianandraina et al. 2015; Senga Kiesse et al. 2017; Sinka et al. 2018), fiber composites (Zah et al. 2007), starch-based polymers (Patel et al. 2006), Bio-based plastics (Tsiropoulos et al. 2015). A review of the literature shows that climate change is the main indicator that has been considered to analyze the environmental impact of hemp shiv as an aggregate for insulation walls (Miller 2018).

This chapter will assess the damage to terrestrial biodiversity and carbon footprint from the production of hemp shiv treated with sol-gel based materials per functional unit (FU) of 1 kg of hemp shiv produced. Treated hemp shiv as a bio-based composite wall with thermal transmittance U-value of 0.15 W m^{-2} K is compared to two other walls with same U-value, which were a wall made with untreated hemp shiv and a reference cavity wall constructed using traditional masonry techniques. Damage to the terrestrial ecosystem due to land use, acidification, photochemical ozone formation, ecotoxicity, water use and climate change were included. Data on hemp production were obtained from hemp farmers from CAVAC, an agricultural

Table 5.6 Characteristics of walls and materials used

Scenario	Material	Unit	Value	Comment
Reference wall	Solid brick	kg	183.6	Clay brickl market for l cut-off, U
	Air cavity	kg	_	None
	Eco-therm insulation	kg	11.6	Kingspan insulation panel
	Cement block	kg	200.0	Concrete block l market for l cut-off, U
	Gypsum plasterboard	kg	8.7	Gypsum plasterboard l market for l cut-off, U
	Gypsum plaster	kg	2.1	Stucco l market for l cut-off, U
Treated bio-composite wall	Treated hemp shiv	kg	61.8	82% Hemp shiv and 18% Sol-Gel
	Water	kg	101.3	Tap water l market for l cut-off, U
	Bio-based binder	kg	91.2	Tradical ThermO, modelled on SimaPro
	Timber frame	kg	9.3	Plywood, for outdoor use l market for l cut-off, U
	Steel fastening	kg	5.0	Steel, unalloyed l market for l cut-off, U
Untreated bio-composite wall	Untreated hemp shiv	kg	50.7	100% hemp shiv
	Water	kg	152.0	Tap water l market for l cut-off, U
	Bio-based binder	kg	91.2	Tradical ThermO, modelled on SimaPro
	Timber frame	kg	9.3	Plywood, for outdoor use l market for l cut-off, U
	Steel fastening	kg	5.0	Steel, unalloyed l market for l cut-off, U

cooperative based in west France. Potentially disappeared fraction of species (PDF), as a damage to the terrestrial biodiversity, integrated over area and time in m^2 year, was analysed for the functional unit of 1 kg of hemp shiv and sol-gel produced and subsequently per one square meter of insulation wall with a U-value of 0.15 W/m^{-2} K for 1 year of its service life.

Treated hemp shiv as a bio-composite in a hypothetical building wall was compared to two other hypothetical walls, including a wall with untreated hemp shiv and a cavity wall as a reference wall. The dimensions of the walls were calculated in order to have a U-value of 0.15 W/m^{-2} K. Table 5.6 shows the characteristics of the walls of interest in this study, along with their materials used. The wall with bio-composite has been made up with treated and untreated hemp shiv, bio-based binder and water. A timber frame and steel fixings are used as the load-bearing structural elements. The wall with bio-composite has been made up with treated and untreated hemp shiv, bio-based binder and water. A timber frame and steel fixings are used as the load-bearing structural elements.

Table 5.7 Terrestrial ecosystem damage (Potentially disappeared fraction PDF m^2 year/kg) from the production of 1 kg of hemp shiv, based on hierarchist perspective

Impact category (PDF m^2 year/kg)	Value	
	EA	MA
Land use	0.532	0.863
Terrestrial acidification	0.018	0.027
Ozone formation	0.007	0.011
Terrestrial ecotoxicity	0.001	0.001
Water	0.001	0.001
Global warming	−0.308	−0.292

Economic allocation (EA) and mass allocation (MA) show the results based on economic and mass allocation

Among the environmental impacts, global warming has a negative impact resulting from the sequestered carbon during hemp production (agricultural stage). In spite of the carbon sequestration of hemp production, the agricultural stage is the main contributor to all of the impact categories for hemp shiv production. Table 5.7 shows the total damage to terrestrial biodiversity of 1 kg hemp shiv production. As it can be seen from Table 5.7, depending on allocation methods, the results vary. The environmental damage associated with mass allocation is greater than those analysed based on economic allocation. The carbon footprint of 1 kg hemp shiv was calculated as −1.55 kg CO_2-eq/kg and −1.63 kg CO_2-eq/kg, based on mass and economic allocation respectively. Carbon footprint of common insulation materials for building has been reported as: 7.336 kg CO_2-eq/kg for expanded polystyrene (EPS) foam slab, 1.511 CO_2eq/kg for rock wool, 6.788 CO_2-eq/kg for polyurethane rigid foam, 0.807 kg CO_2-eq/kg for cork slab, 1.831 kg CO_2-eq/kg for cellulose fiber and 0.124 kg CO_2-eq/kg for wood wool (Zabalza Bribian et al. 2011; Lopez Hurtado et al. 2016).

Figure 5.10 shows the total damage to terrestrial biodiversity by using 1 kg of hemp shiv, based on regionalized and generic (world average) characterization factor for hierarchist perspective. Since climate change and terrestrial ecotoxicity results are purely based on generic values. The damage to terrestrial biodiversity based on regionalized characterization factors shows greater values than generic ones. The main differences come from the impact of land use.

Carbon footprint of one square meter of a wall, using treated and untreated hemp shiv was calculated using IPCC 2013 GWP 100a method. Using economic allocation, the total carbon footprint of 1 m^2 of treated hempcrete wall (for its entire service life) is 24.65 kg CO_2-eq and 22.51 kg CO_2-eq based on end of life treatment as composting and landfilling respectively. The results based on mass allocation and untreated hempcrete wall are shown in Fig. 5.11.

Table 5.8 shows the carbon footprint of treated and untreated hempcrete wall of current study compare to similar studies. The current study considered a U-value of 0.15 $W/m^2 \cdot K$ for all scenarios which requires a thicker wall compared with similar studies.

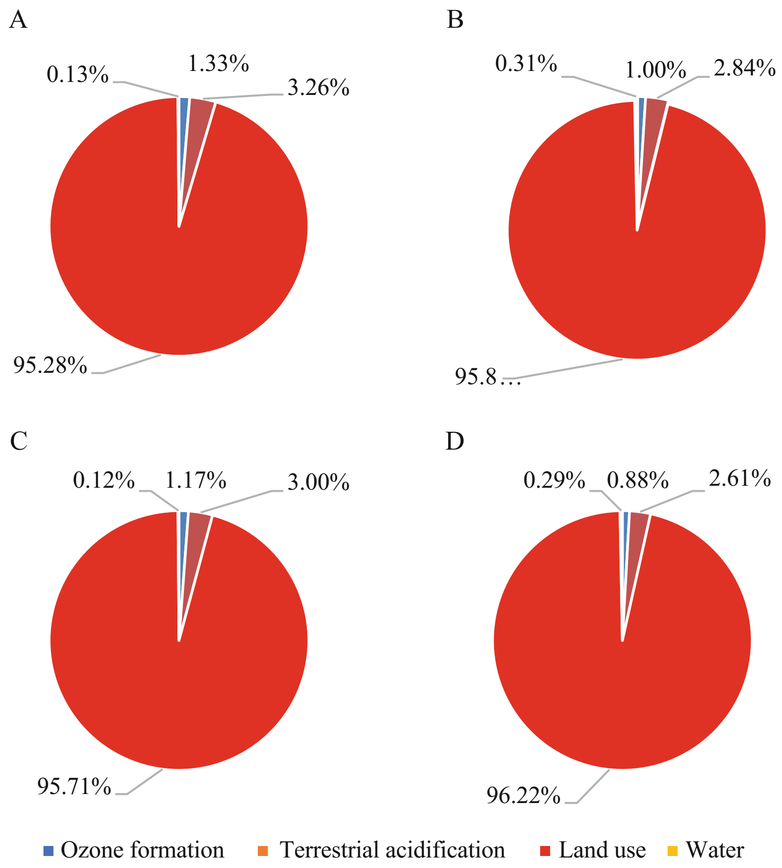

Fig. 5.10 Terrestrial biodiversity of 1 kg of hemp shiv, based on regionalized and generic (world average) characterization factor for hierarchist perspective. (**a**) Regionalized values and economic allocation; (**b**) Generic values and economic allocation; (**c**) Regionalized values and mass allocation; (**d**) Generic values and mass allocation

5.7 Conclusions

A systematic assessment of both commercially available bio-based building products and key raw materials was undertaken as part of the ISOBIO Project. This assessment provides a unique database of biogenic materials, their construction relevant properties and environmental footprints. The assembly of these raw materials into composite core structures is enabling a materials-by-design approach to be developed. Both biogenic and mineral binders are being used to provide a toolkit of composite materials and their key characteristics. Novel chemistries are being developed to provide high levels of water repellence to enable products with durability to external conditions, and to improve the fire resistance of these

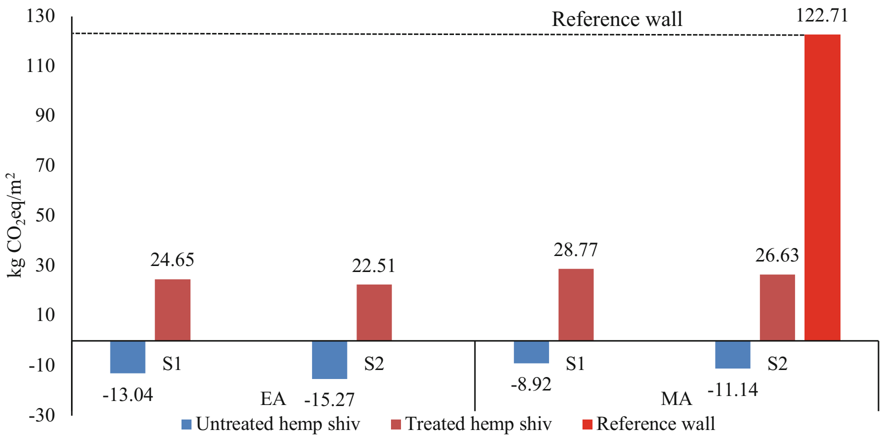

Fig. 5.11 Carbon footprint of 1 m^2 walls for their entire service life. EA and MA show the results based on economic and mass allocation. S1 and S2 are waste scenarios (S1: composting hemp shiv and landfilling the rest, S2: landfilling all the materials)

Table 5.8 Comparison of carbon footprint of similar studies on hempcrete walls with the current study

Type	Wall thickness (mm)	U-value ($W/m^2 \cdot K$)	Carbon footprint (kg CO_2-eq)	References
Hempcrete wall	260	0.42	−35.53	Boutin et al. (2006)
Hemp-lime wall	300	0.19	−36.08	Ip and Miller (2012)
Hempcrete wall	240 + 10[a]	0.36	−1.60	Pretot et al. (2014)
Hempcrete wall	250	0.27	−12.09	Arrigoni et al. (2017)
Untreated hempcrete	507	0.15	−15.27 to −8.92	Current study
Treated hempcrete	507	0.15	22.51–28.77	Current study

[a]This study has 10 mm of coating

composites. Adoption of bio-based materials for the construction sector is dependent on many factors including material performance (real and perceived), availability, cost, regulatory incentive. The ISOBIO project is establishing a database of raw materials and composites, a full environmental assessment of key products and appropriate test methods that enable the advantages of bio-aggregates to be quantitatively measured and compared with conventional materials. These steps are aimed at providing a robust platform to enable the industrial partners to take the emerging products to the market-place by overcoming many of the barriers to adoption that currently exist.

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