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Life cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks

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ABSTRACT

Hempcrete is a natural building material that, in recent years, has known an increased popularity in a number of European countries. Hempcrete-based construction materials are used in non-bearing walls, as finishing plasters and floor/roof insulators. In the present work, the environmental performances of a non-load-bearing wall made of hempcrete blocks were assessed via Life Cycle Assessment (LCA). The analysis encompassed the whole life cycle but the end of life, due to the lack of reliable data for this stage. The production phase of the raw materials was identified as the main source of environmental impacts, but the transport distance of raw materials, as well as the amount and composition of the binder mixture, can considerably affect the results. An experimental assessment (via X-ray Powder Diffraction analysis) of the carbonation process taking place within the binder during the use phase of the wall showed that the carbonation rate may be smaller than assumed in previous works: after 240 d, only the outermost layers of the blocks showed significant levels of carbonation, while the innermost layers experienced only a negligible increase in the amount of carbonates. Nevertheless, the overall emission balance is very favourable: thanks to biogenic CO_2 uptake during hemp growth and to CO_2 uptake by carbonation, hempcrete blocks have a negative carbon footprint and act therefore as effective carbon sinks.

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1. Introduction

Globally, the extraction of minerals used in the construction sector has enormously increased during the 1900s and even more in the early 2000s (Krausmann et al., 2009): from 18.8 Gt/y in 2000 to 37.9 Gt/y in 2013 (WU, 2016). The strongest increase has been observed in the extraction of cement-related minerals and, although this enormous use of non-renewable resources has slightly slowed down in the EU during the last decade due to the serious downturn experienced by the industrial and construction sectors for the global economic crisis, 13.3 t per capita have still been traded across member state borders in 2013 (Eurostat, 2016a). Moreover, this number does not fully account for raw materials actually extracted from the environment to produce goods. To overcome this gap, the concept of Raw Materials Equivalent (RME), i.e. the amount of raw materials extracted from nature to manufacture a product, has been introduced (Eurostat, 2016b). Notwithstanding the uncertainty underlying the models used to calculate RME, this indicator is largely accepted and gives a more accurate picture of the EU material footprint. Accordingly, raw materials consumption in EU was estimated to be 16.6 t per capita in 2000, steadily increased up to the pre-crisis maximum of 17.6 t in 2007 and rapidly decreased to 14.0 t per capita in 2013. If broken down by material categories (biomass, metal ores, non-metallic minerals, and fossil energy materials) data show that non-metallic minerals, which are mostly composed of construction minerals such as sand and gravel, represent the largest share (from 7.4 to 6.0 t per capita in the 2000–2013 period). Analogously to raw materials extraction, construction industry plays a dramatic role in the anthropogenic global warming. According to the Intergovernmental Panel on Climate Change, buildings are responsible for 19% of the energy-related greenhouse gas (GHG) emissions (IPCC, 2014). Moreover, the construction industry has always been a major sector in the European industry, accounting for 8.5% of the EU-28 GDP, 30.9% of the EU-28 industrial employment and with a 93.5 billion Euro annual turnover (FIEC, 2016). As such, the role of this sector is crucial to the success of European sustainability policies (Pacheco-Torgal, 2014).

To date, the largest efforts to reduce the environmental burden of the construction sector have been devoted to reducing building energy consumption, considering the operational phase as the most impacting of a building life cycle (Cabeza et al., 2014). However, as the reduction of operational energy is achieved by substantially increasing the amount of insulating materials (Ruggieri et al., 2013), the amount of energy embodied into buildings is rapidly increasing (Crawford et al., 2016), partially nullifying the benefits coming from improved thermal efficiency (Blengini and Di Carlo, 2010). A possible strategy to counterbalance this effect is to select building materials with low embodied energy; in this respect, natural materials are perfect candidates, because they are normally undergoing few industrial manufacturing operations, so accumulating low embodied en-

ergy (Melià et al., 2014). An analogous approach is valid for climate change mitigation (Nordby and Shea, 2013): a proper selection of low embodied carbon building materials, possibly characterized by a high carbon storage, is a viable route to help achieve the European target of 20**%** cut in greenhouse gas emissions (from 1990 levels) within 2020. For these reasons, there has been a recent upsurge of interest in bio-based materials at the academic, policy and industry levels (Lawrence, 2015). Those materials incorporate biomasses such as wood, fibre and plant aggregates (Laborel-Préneron et al., 2016). Most of these building materials have been used for centuries, and only in the 20th century they have been displaced by concrete in the construction sector. However, the increased awareness towards global environmental threats, such as climate change, non-renewable resources depletion and water shortage, has renewed the interest of builders associations in more sustainable materials; among these, hempcrete, a lightweight material made of the inner woody core of the hemp plant (hemp shives) mixed with a lime-based binder and water (Bevan and Woolley, 2008), has been rapidly spreading in European countries, such as France, England and, more recently, Italy too (Stanwix and Sparrow, 2014). A recent review (Ingrao et al., 2015) has highlighted many relevant features of hemp-based building materials, which encompass hempcrete, thermo-acoustic insulation panels, and fibre-reinforced composites. To date, however, few studies have investigated the environmental profile of hempcrete: two Life Cycle Assessment (LCA) studies on spray hempcrete (Boutin et al., 2006; Pretot et al., 2014), and one on hempcrete cast between temporary shuttering (Ip and Miller, 2012); none of them has analysed the environmental performances of hempcrete blocks.

To fill in this gap, here an LCA analysis of hempcrete blocks produced by an Italian company, encompassing all production stages except the end-of-life, is presented. Providing additional information to the current state-of-the-art on the employment of hempcrete as a strategy to mitigate the aforementioned environmental impacts, the present study may be of major interest both at the industry and policy levels. In particular, light was cast on a relevant point regarding the emission balance of lime- and cement-based binders undergoing carbonation, i.e. the conversion of calcium hydroxide ($Ca(OH)_2$) present in the binder into calcium carbonate ($CaCO_3$) through the reaction with the carbon dioxide (CO_2) present in the air (Ashraf, 2016). Carbonation increases the mechanical resistance of the bio-composite material and, by absorbing CO_2 during the process, may be relevant for the environmental balance of this product (Grist et al., 2015). Previous studies on hempcrete materials usually took for granted that lime-based binders undergo full carbonation, but never subject this assumption to a quantitative assessment. For this reason, the rate of carbonation was experimentally assessed through X-ray Powder Diffraction (XRPD) analysis to get a more realistic picture of the environmental performances of the building material during the use phase. Two binders were investigated, both employed in current manufacturing practices: the first one was a mixture of dolomite lime and cement; the second was made of dolomite lime only. Finally, an extensive sensitivity analysis was performed to highlight the most relevant factors affecting the environmental performance of hempcrete blocks.

2. Hempcrete block

Hempcrete block is an innovative building product incorporating a large fraction of biomass, with a good performance in thermal and hygrometric regulation. The base of the binder can be hydrated lime, natural hydraulic lime or a mixture of the two. In some cases, a small fraction of cement and/or pozzolanic binder is added to speed up the hardening process and improve the mechanical resistance. Hydrated lime is made from pure limestone and sets through the absorption of CO_2 during the carbonation process. Hydraulic lime is made from limestone with clay impurities (silicates and aluminates) and sets through reaction with water. These processes transform the mixtures into final products that are solid but light, durable and with good insulation performances. Hemp, as any crop, is considered a carbon negative material, because during its growth it absorbs CO_2 from the atmosphere. In addition, the CO_2 captured from the air via carbonation will be stored into the hempcrete block throughout its lifetime and may further improve its environmental profile.

When used in constructions, hempcrete mixtures can easily absorb or release water vapour from the air and have a good vapour permeability. These features allow a better control of thermo-hygrometric conditions in the indoor environment, decrease the risk of vapour condensation and increase thermal comfort. Thanks to the action of lime, hemp shives slowly mineralize, becoming inert and reducing the risks of rot and mould formation (Evrard, 2005). The performances and properties of hempcrete materials depend on the binder, on the quality and length of the hemp shives and on their proportions in the mixtures. Different mixtures produce building materials with different functions. In frame structures, hempcrete mixtures can be used as filling materials in infill walls. If density is increased, the hempcrete mixture allows the production of roof or floor insulation materials; on the other hand, if density is reduced, insulating indoor and outdoor plasters can be produced. The same mixture of hemp and lime can be used to produce prefabricated panels.

Hempcrete block is an interesting product that can be very easily installed, generally requiring mortar to be applied between the blocks (Fig. 1). Hempcrete block walls can be left without any covering or can be covered with finishing plasters, using the same mixture in different proportions. Blocks can be manufactured on the construction site or through an industrial process. Industrial blocks usually have more regular dimensions and a higher quality thanks to an automated manufacturing process and to the employment of more complex mixtures. It is normally assumed by architects and designers that industrial blocks have also better thermo-acoustic performances, but it is difficult to find references on this issue since the performances of blocks constructed on site are difficult to measure.

The installation of rectangular shaped blocks needs staggered and keyed joints, as with other masonry structures. Furthermore, since a vegetal component is included in the mixture, the blocks must be protected from water and rising damp. The joints between the wall and the ground are therefore designed in order to avoid capillary rising as well as water runoff at the wall base. For the same reason, hempcrete blocks are to be installed above the ground level. External walls should be protected by the rain gale with sand and lime plasters in order to avoid rotting of shives.

Blocks are normally self-supporting. As an alternative, it is possible to produce lighter blocks with better thermo-acoustic performances that can equal those of loose mixtures (1:1 binder-to-hemp mass ratio). Lighter blocks need to be installed in a frame structure. Typically, hempcrete blocks are inserted into wood frames, but they can be used also in metal or reinforced concrete structures. Internal partitions made with hempcrete blocks need to be carefully jointed with the external walls. They will normally be thicker than typical internal brick walls (at least 15 cm instead of 8–10 cm). When performing a building retrofit or a building restoration, it is possible to use blocks in external or internal counterwalls to increase thermal insulation. Blocks are normally not used in floors and roofs because mixtures can be easily blown and they are best suited to host the electrical and heating system.

Fig. 1. Details of non-load-bearing walls made of hempcrete blocks: (a) wall erection; (b) side view; (c) front view.

3. Methods

In the present study, carbonation of hempcrete was experimentally assessed via X-ray Powder Diffraction. XRPD outcomes were thus integrated in the environmental profile analysis of the material, assessed via LCA. In this way, the possible benefits in terms of GHG emissions balance could be highlighted. Both the environmental and the experimental characterisation methodologies are presented in the following sections.

3.1. Environmental characterisation: LCA

The LCA was carried out following the international ISO standards (ISO, 2006a, b). The goal of the study was to assess the life cycle environmental impacts of a wall made of hempcrete blocks. The blocks investigated are manufactured by an Italian company (Equilibrium Srl, 2016) with a three-stage production process: mixing of the base constituents, pressing and curing. In the following sections the functional unit (FU), the unit processes and the quality of the data used in the study are presented in detail.

3.1.1. Functional unit

The functional unit (FU) considered was one square meter of non-load-bearing wall made of hempcrete blocks. The overall heat transfer coefficient of the wall (U-value) was 0.27 W/(m^2·K). The thickness of the wall was 0.25 m and one face was in contact with air. No surface coating was considered. Blocks were assumed to be laid manually and mortar was applied between the blocks. Reference flows for 1 FU are shown in Table 1. After drying, the final weight of the FU was estimated to be about 83.9 kg/m^2, considering a density of 330 kg/m^3 and 500 kg/m^3 for hempcrete blocks and mortar, respectively.

Table 1
Reference flows for the functional unit (1 m^2 of non-load-bearing wall made of hempcrete blocks).

Wall component	Hemp shives (kg)	Binder (kg)	Water (kg)	Wet weight (kg)
Hempcrete blocks	31.4	41.1	53.1	125.6
Mortar	0.85	3.40	5.50	9.75

3.1.2. Product system and system boundaries

The following unit processes were considered:

1. Hemp shives production (crop production and transformation)
2. Binder production (minerals extraction and transformation)
3. Transport of raw materials to the manufacturing company
4. Hempcrete blocks production processes (including packaging)
5. Transport of hempcrete blocks to construction site
6. Wall construction (mortar production and wall erection)
7. Use phase (carbonation)

In unit process 4, water and energy consumptions were accounted for, as well as the production of packaging and its transport to the manufacturing site. Unit process 6 comprises the extraction of raw materials for the production of mortar, their transport to the construction site, and water and energy consumption on site.

Carbonation was the only process considered in the operational phase of the block (unit process 7). The absence of coating on the wall system spares the maintenance work taken into account in a previous study (Pretot et al., 2014). The carbonation process improves the mechanical properties of the biocomposite over time: therefore, no substitution of the material during the building's lifetime is expected. At the building end-of-life, the material can be crushed and used again as filler for insulation. Crushing would speed up the carbonation process of the unreacted calcium hydroxide. To our knowledge, however, no hempcrete structure has already been dismantled up to now; the end-of-life phase was thus excluded from the system boundaries. Nevertheless, the CO_2 absorbed by the material during the production and use phases will most likely remain stored within the material also after the end of the building's life.

3.1.3. Data sources and allocation procedure

The production site of hempcrete blocks is located in northern Italy; all data regarding the manufacturing processes inside the factory ("from gate to gate") and the information regarding raw materials transports were provided by the producer. Secondary data were used in the inventory of mixture components: a previous LCA study on hemp cultivation (Zampori et al., 2013) was the source for the

hemp shives processing data, while the Ecoinvent database (Weidema et al., 2013) was used for the binder production processes.

The cut-off system model, which attributes the environmental impacts of the primary production of a material to its primary user, was adopted to allocate the burdens among users (Weidema et al., 2013). The system model was chosen in accordance to the one followed by the International EPD® System when certifying the life cycle environmental impacts of a product (Environdec, 2013). Considering the rapidly growing number of companies in the construction sector interested in certifying their products (Passer et al., 2015), the methodology was here adopted in order to have a common ground for comparison with other building components. On the other hand, the allocation procedure among co-products is extensively presented for the case of hemp shives in the life-cycle inventory section (4.1) and in the sensitivity analysis (6.4).

3.1.4. Impact indicators

The impact assessment was carried out using the environmental impact categories recommended by the European standard (CEN, 2012): abiotic depletion (ADP), fossil fuels depletion (ADP fossil), global warming over a time interval of 100 y (GWP), ozone depletion (ODP), acidification (AP), eutrophication (EP), photochemical ozone creation (POCP). Characterisation factors are those proposed by the Institute of Environmental Studies of the University of Leiden for the method CML-IA Baseline (version 3.04) (Leiden University, 2016). Additionally, environmental impacts were assessed in terms of Cumulative Energy Demand (CED, version 1.09) (Frischknecht et al., 2015) and with the Greenhouse Gas Protocol method (GGP, version 1.02) (World Resources Institute, 2012).

3.2. Experimental characterisation: carbonation via XRPD

The progress of the carbonation process over time was investigated in two hempcrete blocks, differing in the composition of the binder. The first one, which was the base case for our study and is the one currently on the market, had a binder composition of 80% (by mass) dolomite lime and 20% cement. In the second one, the binder was composed of dolomite lime only. The rate of carbonation in the second block was assessed to understand how a different composition of the binder would affect the CO_2 absorption of the building material. Analyses were performed via semi-quantitative X-ray Powder Diffraction. The phase composition of samples extracted was assessed at regular time intervals from brick production up to 8 months (30, 75, 110, 150 and 240 d). Carbonation was monitored at different depths within the block: at each time interval, 5 samples were extracted at different depths (0–2, 2–4, 4–6, 6–8 and 8–10 cm), crushed and sieved to separate the binder from the hemp. Fig. 2 shows a sketch of the block and the position of the sampling points.

The XRPD pattern of each fraction was recorded with a Bruker D8 Advance Diffractometer using graphite monochromated Cu Kα radiation. The measurement interval was 10–50 °2θ, with measurement steps of 0.02 °2θ and a measurement time of 1 s/step. The peaks used for the semi-quantitative analysis were the (*001*) peak of $Ca(OH)_2$ at 2θ = 18.048, the (*001*) peak of $Mg(OH)_2$ at 2θ = 18.587, the (*104*) peak of $CaCO_3$ (Calcite) at 2θ = 29.406, the (*112*) peak of $CaCO_3$ (Vaterite) at 2θ = 27.048 and the (*200*) peak of MgO at 2θ = 42.917. The single peaks used for the semi-quantitative analysis were also recorded with a measurement time of 4 s/step to increase the counting statistics. The integrated intensities of the reported peaks were evaluated via peak profile fitting of the experimental data, performed with the software Topas+ 2.1 (Bruker AXS®) using a Pseudo-Voigt profile function. The obtained integrated intensities were used for the semi-quantitative analysis of phases using the generalised Reference Intensity Ratios (RIR) method. Provided that all the phases are taken into account, the intensity of the peaks can be related to the amount of each phase in the mixture through the generalised RIR equation (Lifshin, 2008):

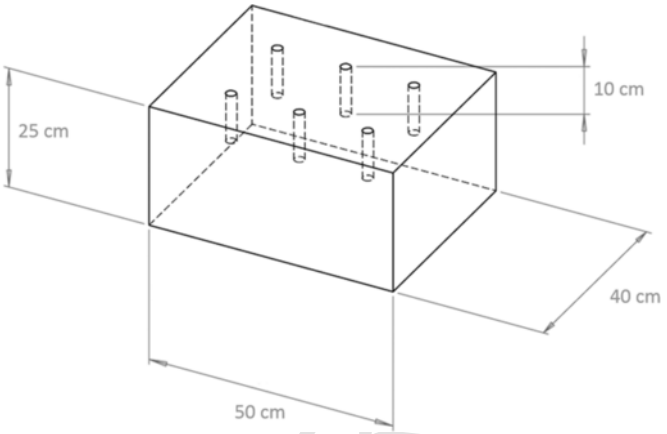

Fig. 2. Location of the sampling points used to monitor the carbonation process within the hempcrete block.

$$\chi_\alpha = \frac{I_{i\alpha}}{RIR_\alpha I_{i\alpha}^{rel}} \left(\frac{1}{\sum_{k=1}^{n(phases)} \frac{I_{i,k}}{RIR_k I_{i,k}^{rel}}} \right)$$

where χ_α is the weight fraction of the phase α, $I_{i\alpha}$ is the integrated intensity of the i^{th} peak of the phase α, RIR_α is the Reference Intensity Ratio of the phase α with respect to corundum (literature values were adopted) and $I_{i\alpha}^{rel}$ is the relative intensity of the i^{th} peak with respect to the most intense peak of the same phase *α*. The results of the semi-quantitative analysis of each portion were then used to evaluate the amount of calcium hydroxide and calcium carbonate at each depth in the block and finally in all the block body.

4. Life cycle inventory

4.1. Hemp

Data regarding hemp cultivation and shives production (Zampori et al., 2013) were collected directly from the Italian producer supplying the block manufacturer considered in this study. A hemp yield of 15 t/(ha·y) was considered and a mass allocation was applied to subdivide the impacts among the co-products of hemp cultivation. The mass outputs considered were: 75% shives, 20% fibres and 5% dust. An economic allocation among co-products was considered as well in the sensitivity analysis. Considering a concentration of 0.5 kg of carbon per kg of dry matter, 1.84 kg of CO_2 were stoichiometrically calculated to be sequestered per kg of dry hemp through photosynthesis during the plant growth (Pervaiz and Sain, 2003). Impacts arising from the indirect land use change (ILUC) caused by hemp cultivation were not included in the study, due to the high level of uncertainty that still affects the modelling of this aspect (De Rosa et al., 2016).

4.2. Binder

The binder used in the block's mixture is made of 80% dolomite lime and 20% cement. Dolomite lime is a hydrated lime obtained from the calcination process of the dolostone, a sedimentary carbonate rock composed predominantly of the mineral dolomite. Dolomite is a naturally occurring mineral, composed of calcium magnesium carbonate, with abundant reserves around the world (Warren, 2000). Since no primary data were available for the dolomite calcination process, Ecoinvent data related to ordinary hydrated lime were used for the study. When exposed to air, the calcium hydroxide (portlandite) present in the binder fixes CO_2 due to the carbonation reaction. The maximum amount of CO_2 that the binder can absorb over its lifetime is calculated considering that all the portlandite in the mixture will carbonate. Portlandite is both a product of the slaking of quicklime, the precursor of hydrated lime, and of cement hydration. Thus, the maximum amount of CO_2 uptake is calculated through the following equation:

$$Max\ \ CO_2 uptake = \left(DL \times p_{DL} \times \frac{M_{CO_2}}{M_p}\right) + \left(C \times c_C \times \frac{M_{CO_2}}{M_c} \times 0.75\right)$$

where DL is the mass of dolomite lime in the binder, p_{DL} the weight fraction of portlandite in the dolomite lime, C is the mass of cement in the binder, M_p, M_c *and* M_{CO_2} are the molar weights of portlandite (p), calcium oxide (c) and CO_2 respectively, c_C the weight fraction of calcium oxide in cement and 0.75 the fraction of calcium oxide in cement that carbonates (Lagerblad, 2005). The amount of CO_2 absorbed by the blocks over time was measured through XRPD analysis, as explained in section 3.2.

4.3. Blocks production

The production process of hempcrete blocks is summarised in Fig. 3. Once arrived to the company gate, hemp is stocked in a storage room and lime is stored in silos. From the storage place, the two components of the hempcrete block are sent to a blending machine, where they are mixed with water. The energy consumption of the blending machine is 0.776 kWh per cycle. Every cycle produces 0.6 m^3 of hempcrete mixture. After mixing, the mixture is sent through a conveyor belt to the pressing machine that will shape the hempcrete blocks. The consumption of a pressing cycle is 0.306 kWh per 0.1 m^3 of mixture. Once pressed, blocks are piled on shelves to cure. In the curing time, necessary to give the block enough strength, the blocks lose about half of their weight. No forced ventilation is used to speed up the hardening process. No waste is produced during the production cycle because all the residues are used as input materials in the following cycles. Once cured, the blocks (in 2 m^3 batches) are loaded on pallets and wrapped up with 0.6 kg of polyethylene packaging film and 0.4 kg of polypropylene straps, ready to be transported on site.

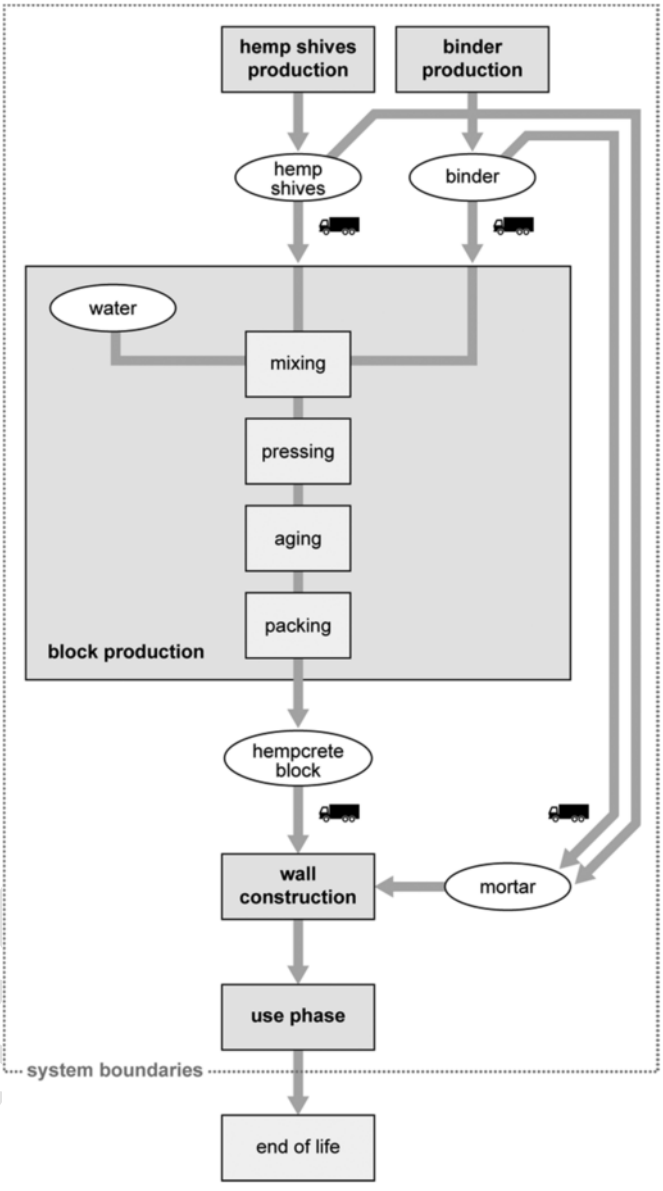

Fig. 3. Process scheme of hempcrete block production.

5. Results

5.1. Carbonation

In both samples, the amount of carbonates in the blocks increased with the sample age. The carbonation rate strongly depended on the sampling depth: in the sample composed only of dolomite lime the amount of carbonates increased rapidly in the outermost layer (0–2 cm) from about 15% (by mass) of the binder at 30 d to about 50% after 240 d, mainly at the expense of $Ca(OH)_2$ that showed an opposite trend. In the second layer (2–4 cm), the amount of carbonates increased significantly only after 150 d of ageing, while in the innermost layers the carbonation was very limited: an increase in carbonates could be detected at a depth of 4–6 cm only after 8 months, while it was still negligible below 6 cm depth at any age. The base case sample, containing both dolomite lime and cement, showed a similar behaviour both in time and in depth, except that the amount of

carbonates was higher in absolute terms due to the higher initial content of carbonates in the binder. Overall, assuming 1 face exposed to air, the amount of CO_2 captured after 240 d was estimated to be 7 g per kg of binder for the sample containing just dolomite lime and 12 g per kg of binder for the block containing also cement.

5.2. Life cycle impact assessment

In the following sections, the results of assessing the environmental impact of a wall made of hempcrete blocks according to the impact indicators listed in section 3.1.4 are reported and discussed. All results refer to the first type of binder, i.e. the mixture of dolomite lime and cement. For simplicity, some of the unit processes listed in section 3.1.2 are grouped together: in particular, the transport of the raw materials to the manufacturing company and the transport of manufactured hempcrete blocks to the construction site are grouped under the category "transport". As stated in section 3.1.2, the uptake of CO_2 during carbonation is the only effect accounted for in the use phase (unit process 7). Accordingly, the operational phase appears in the assessment of life cycle impacts only when the GGP method is used.

5.2.1. CML-IA baseline

Fig. 4 summarises the environmental impacts of 1 m^2 of wall made of hempcrete blocks according to CML-IA Baseline characterisation factors (see Table S1 in the Supplementary Information for detailed results). The binder production process was the main cause of impacts for all the categories considered, except for abiotic depletion; in particular, lime calcination and clinker production were the main sources of emissions for this process. Another important source of environmental impacts was the transport phase, mainly due to diesel consumption. An important share of diesel consumption, responsible for the depletion of abiotic fossil resources, was due to the functioning of the machineries used in the hemp shives production. The main responsible for abiotic depletion was the consumption of lead and cadmium in the electricity generation process. The process that requires more electricity from the grid was the manufacturing of hempcrete blocks inside the company; nevertheless, energy use during block production was minimal if compared to that necessary for binder production (mainly thermal energy).

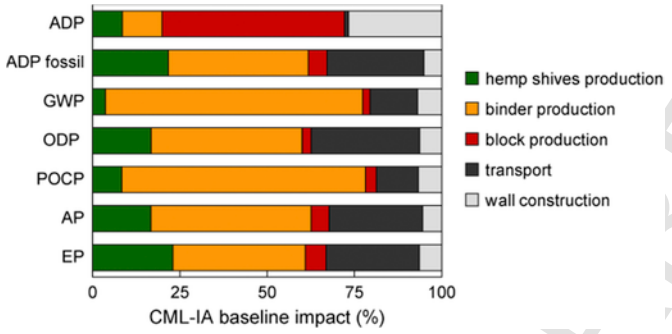

Fig. 4. Life cycle impact assessment of 1 m^2 of hempcrete wall. Percentage contribution of the different unit processes to CML-IA baseline impact categories.

5.2.2. Cumulative Energy Demand (CED)

The results of the impact assessment analysis in terms of cumulative energy demand are summarised in Fig. 5 and detailed in the Supplementary Information (Table S2). In absolute terms (Fig. 5a), the major share of energy embodied in the wall came from renewable sources, due to the significant presence of hemp shives in the blocks and in the mortar (Fig. 5b). In this respect, it is important to underline that the binder-to-hemp ratio in the brick is expressed as a mass ratio: as the density of hemp shives is lower than that of the binder, the volume occupied by shives is much higher. Another important share of the cumulative energy demand came from the consumption of non-renewable (fossil) energy sources, mainly associated to the production of the binder and the transport phase. Energy from nuclear and other renewable sources (wind, water and sun), which represented a minor fraction of the total energy demand, was mainly due to electric consumption and could be ascribed to the nuclear and renewable components of the Italian electricity generation mix.

5.2.3. Greenhouse Gas Protocol (GGP)

The budget of greenhouse gas emissions associated with the functional unit is reported in Table 2. Non-biogenic (fossil) emissions and CO_2 uptake represented the two major terms of the budget, while emissions from biogenic sources and land transformation were negligible. The main source of fossil emissions was the calcination of lime, which takes places in kilns at very high temperatures. In contrast, CO_2 uptake was the result of photosynthetic and carbonation processes: hemp absorbed CO_2 during its growth, while the binder started absorbing CO_2 after it got in contact with air during the mixing process. After 240 d from block production, part of the binder already carbonated and additional CO_2 was absorbed by the wall. The emission balance after 240 d was hence negative, equal to a net absorption of 12.09 kg CO_2-eq per square meter of hempcrete wall. This means that the wall acted as a carbon sink, stocking more CO_2 than it was emitted during the production. If the wall were completely carbonated, the emission balance would have been equal to −26.01 kg CO_2-eq/m^2.

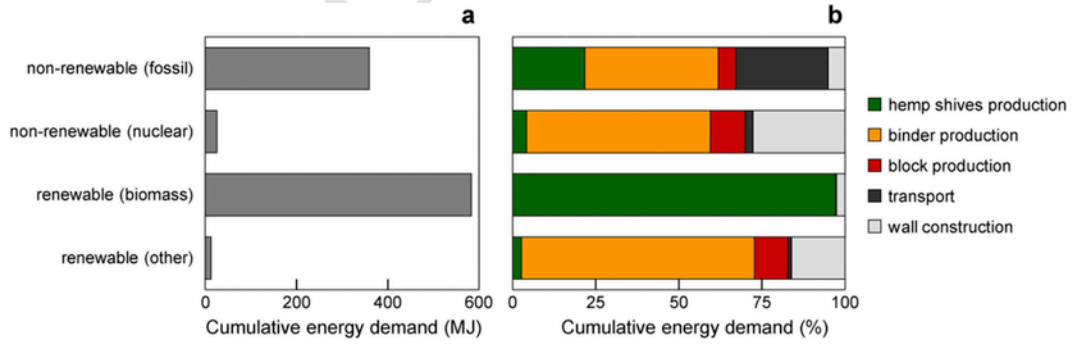

Fig. 5. Cumulative energy demand of 1 m^2 of wall made of hempcrete blocks. (a) Breakdown by energy component. (b) Percent contribution of each unit process.

Table 2
Greenhouse gas emissions and CO_2 uptake of 1 m^2 of wall made of hempcrete blocks calculated using the Greenhouse Gas Protocol method (see section 3.1.2 for the description of unit processes). As for the CO_2 uptake, the value reported for the use phase refers to 240 d since the block production, while the value indicated between parentheses refers to the completion of the carbonation process.

Impact category	Unit	1. Hemp shives production	2. Binder production	4. Block production	3+5. Transport	6. Wall construction	7. Use phase	1-7. Total
Fossil	kg CO_2 eq	1.75	35.40	1.02	6.52	3.32	–	48.02
Biogenic	kg CO_2 eq	0.01	0.18	0.03	0.01	0.10	–	0.34
Land use	kg CO_2 eq	0.00	0.00	0.00	0.00	0.00	–	0.00
Uptake	kg CO_2 eq	58.0	0.04	0.04	0.01	1.51	0.53 (14.45)	59.60

6. Sensitivity analysis

A sensitivity analysis was performed to assess the robustness of the results of the life cycle impact assessment to the most critical assumptions of the analysis. To this end, a number of alternative cases were generated (summarised in Table 3) by varying one or more basic assumptions regarding, in particular, the binder mixture (section 6.1), the transport distances (section 6.2), the binder-to-hemp mass ratio of the blocks (section 6.3) and the allocation factors (section 6.4).

6.1. Binder mixture

The reference binder mixture for our study was composed of dolomitic lime (80% by mass) and Portland cement (20%). Cement is added to the mixture in order to speed up the hardening process and reduce the curing time of the blocks at the manufacturing site. The addition of cement smooths out the production process and allows a quicker installation of the product. However, blocks are not meant to be load-bearing and therefore cement could in principle be removed from the mixture if the curing process could be suitably modified. The choice of the binder may also affect other properties of the building material than sustainability and load-bearing capacity: some authors, for example, affirmed that hemp concretes made with cement have a lower thermal conductivity (λ_{dry} 0.059 W/(m·K)) than equivalent materials made with lime (λ_{dry} 0.078 W/(m·K)) or hydraulic lime (λ_{dry} 0.076 W/(m·K)) (Gourlay and Arnaud, 2010). The environmental consequences of substituting cement as a component of the binder were assessed by comparing three different mixtures (see Table 3): the base binder (case A), a binder composed of pure dolomitic lime (case B) and a mix of hydrated lime, hydraulic lime and pozzolan (case C). Case B refers to the mixture used also for the carbonation analysis and reflects the possibility of completely removing cement from the mixture, while case C refers to a mixture inspired to the studies of Ip and Miller (2012) and Pretot et al. (2014). Emissions for the pozzolan were taken from the literature (Heath et al., 2014), assuming that the pozzolanic material used in the mixture was metakaolin (Walker and Pavía, 2014). According to Pretot et al. (2014), a maximum CO_2 uptake of 0.107 kg per kg of hydraulic lime was considered. As the carbonation rate was estimated through XRPD analysis only for case A and B, for case C the same carbonation rate as in case A was assumed.

6.2. Transport distances

The basic assumption (case A) regarding the transport phase was that hemp shives were supplied by an Italian producer (located 245 km away from the blocks' manufacturing site) and that the binder was supplied by a quarry located 320 km away. Due to different national regulations, hemp shives sold in France are more uniform than those sold by the Italian hemp supplier. For this reason, the block manufacturer has recently opted in favour of using French hemp in the mixture. The consequences of this choice on the environmental performances of the wall were estimated by considering two alternative cases: one (case D1) in which hemp was considered to be produced in France (with a transport distance of 750 km), but with production emissions equal to those of the Italian producer, and one (case D2) in which the production emissions considered were those reported by Boutin et al. (2006) for an average French producer. As for the transport of the binder, a more favourable scenario in which the binder was supplied by a quarry closer to the manufacturing site (40 km away) was also considered (case E). The distance between the production site and the construction site was kept equal to that of the base case (100 km) for all cases.

6.3. Binder-to-hemp mass ratio

The binder-to-hemp mass ratio was set to 1.3:1 (1.3 kg of binder per 1 kg of hemp) in the base case (A). However, manufacturers produce hempcrete blocks with different mass ratios according to their expertise and to the function the building material has to fulfil. The binder-to-hemp mass ratio may vary considerably, ranging from 2.2:1 to 1:1, leading to variations in the density of the blocks and to differ-

Table 3
Parameters varied in the scenarios considered in the sensitivity analysis. Scenario A is the reference case; details about the other scenarios are given in section 6.

Scenario	Binder mixture components (% by mass)					Transport distances		Hempcrete blocks		Allocation method
	Dolomitic lime (%)	Hydrated lime (%)	Hydraulic lime (%)	Portland cement (%)	Pozzolan (%)	Hemp (km)	Binder (km)	Binder-to-hemp mass ratio (kg/kg)	Density (kg/m^3)	
A	80	–	–	20	–	245	320	1.3	330	Mass
B	100	–	–	–	–	245	320	1.3	330	Mass
C	–	75	15	–	10	245	320	1.3	330	Mass
D1	80	–	–	20	–	750	320	1.3	330	Mass
D2	80	–	–	20	–	750	320	1.3	330	Mass
E	80	–	–	20	–	245	40	1.3	330	Mass
F	80	–	–	20	–	245	320	2.0	360	Mass
G	80	–	–	20	–	245	320	1.0	312	Mass
H	80	–	–	20	–	245	320	1.3	330	Economic

ent physical properties (e.g. load-bearing capacity, hygro-thermal behaviour). Given the lower density of hemp shives compared to the binder, a lower ratio results in lower densities if the volume of the block and the water-to-solids mass ratio in the mixture are kept constant. Density usually varies between 300 and 450 kg/m^3, but in exceptional cases, such as the one of a Spanish manufacturer (Cannabric, 2016), blocks could reach densities over 1000 kg/m^3. The goal of the present analysis was to understand whether a variation in the amount of shives in the mixture would considerably affect the overall environmental impact of the blocks, considering that the resulting wall could have different properties and therefore a different function. Two alternative cases were considered: a heavier mixture with a binder-to-hemp mass ratio 2:1 (case F) and a lighter one with a binder-to-hemp mass ratio 1:1 (case G). The water-to-solids mass ratio in the block mixture was kept constant: equal to 0.73 in the wet mixture and equal to 0.09 in the cured blocks.

6.4. Impacts allocation

Where allocation of the impacts among co-products cannot be avoided, the ISO standard encourages partitioning the inputs and outputs of the system according to underlying physical relationships (ISO, 2006b). When co-products have a market value different from the determining product (i.e. the product that determines the production volume of the activity), a revenue allocation would be fairer though. In the present study, allocation was applied among the co-products of hemp cultivation and the difference on the environmental impacts considering a physical (i.e. mass) and an economic allocation for hemp production was investigated. Mass allocation, with factors presented in section 3.1, was used for case A, while economic allocation, with factors based on average prices for shives, fibres and dust considered in a previous work (Zampori et al., 2013) (0.25, 0.60 and 0.00 €/kg, respectively) was used for case H. Although fossil CO_2-eq emissions were economically allocated, the amount of CO_2 uptake was mass-allocated among the three products because it is a strictly physical quantity.

6.5. Results

The outcomes of the sensitivity analysis are summarised in Table 4. The variation among results obtained under alternative assumptions is expressed in terms of percentage differences with respect to the base case (A).

The choice of the binder affected moderately the overall environmental impacts of hempcrete: substituting cement with lime (case B) brought no perceivable environmental benefit in any of the considered environmental categories but eutrophication (−17.1%) and acidification (−8.7%), due to the higher emissions of nitrogen oxides during the clinker production process with respect to lime production process. On the other hand, the use of lime instead of cement led to higher CO emissions in the calcination process and a consequently higher formation of photochemical ozone (+9.4%). In contrast, using hydrated lime and hydraulic lime instead of dolomitic lime (case C) led to a higher uptake of CO_2 (+8.2%) during the use phase, because hydrated lime is composed entirely of portlandite available for carbonation while in the dolomitic lime portlandite represents only about 50% of the binder's mixture. The anomalous increase in abiotic depletion (case C) was probably due to the fact that impacts from metakaolin were taken from the literature (Heath et al., 2014); this fact makes difficult to check the original data sources and explains different outcomes.

The recent decision of using French hemp by the Italian manufacturer led to a general increase of all the impacts (case D1) when environmental impacts of hemp shives production equal to the base case were considered. In four categories, i.e. ADP fossil, ODP, AP, and EP, the increase was over 10%. When, in contrast, the impacts estimated by Boutin et al. for hemp production in France were considered (case D2), there was a wide difference in some of the impact categories, for instance ADP. In this case, the use of different databases for secondary data (Ecoinvent 2 vs Ecoinvent 3) and differences in agricultural practices between France and Italy were certainly the source of discrepancies. Indeed, all impact categories except eutrophication worsened, in particular abiotic depletion, which increased of four orders of magnitude. Vice versa, the procurement of lime from a quarry closer to the manufacturing site (case E) reduced all impacts by an average 5%. A reduction of the binder-to-hemp mass ratio from 1.3:1 to 1:1 (case G) led to an average impact reduction of ca. 7%. Besides environmental impacts, the reduction in the use of binder would result in a lighter mixture with presumably better hygro-thermal properties but worse mechanical resistance. Conversely, increasing the binder-to-hemp mass ratio to 2:1 (case F) led to higher environmental impacts (+13% on average compared to case A). Moreover, a higher density would produce a mixture with presumably better structural properties but worse hygro-thermal characteristics.

Finally, even though allocation of the impacts on the co-products is a key factor in attributional LCA analysis, considering an economic allocation for hemp production co-products (case H) did not lead to a sensible variation in the results of our study. This was due to the low environmental impact of hemp production compared to the binder's production process. Nevertheless, the economic allocation further stressed the benefits of using a by-product (i.e. hemp shives), leading to a 5% average reduction of the overall environmental impacts.

The GWPs of all sensitivity scenarios are shown in Fig. 6, highlighting the different contributions to GHG emissions. Emissions from fossil sources and land use transformation were counterbalanced by the biogenic uptake due to hemp shives in all scenarios but F, demonstrating the relevance of the binder to the environmental performance. Instead, CO_2 uptake from short-term carbonation (240 d) had a negligible relevance, i.e. less than 4% with respect to full car-

Table 4
Results per FU relative to the seven impact categories recommended by EN 15804; for completeness, CO_2 uptake, including both biogenic uptake and the amount from full binder carbonation, is listed separately.

Impact category	Unit	A	B	C	D1	D2	E	F	G	H
ADP	mg Sb eq	1.75	1.61	15,101.48	1.75	36,321.24	1.74	1.78	1.73	1.73
ADP fossil	MJ	358.73	359.44	348.08	401.90	389.78	332.52	396.19	337.03	343.82
GWP	kg CO_2 eq	48.04	47.88	45.88	50.87	49.08	46.33	58.41	42.03	47.70
CO_2 uptake	kg CO_2 eq	74.04	73.29	80.08	74.04	82.36	74.03	68.61	77.19	74.04
ODP	mg CFC-11 eq	3.93	4.09	3.97	4.46	4.70	3.61	4.42	3.65	3.80
POCP	g C_2H_4 eq	6.84	7.48	6.63	7.20	7.53	6.62	8.18	6.06	6.73
AP	g SO_2 eq	81.33	74.28	79.82	90.79	143.02	75.35	91.80	75.26	78.74
EP	g PO_4^{3-} eq	15.82	13.12	14.43	17.66	13.94	14.65	17.36	14.94	15.13

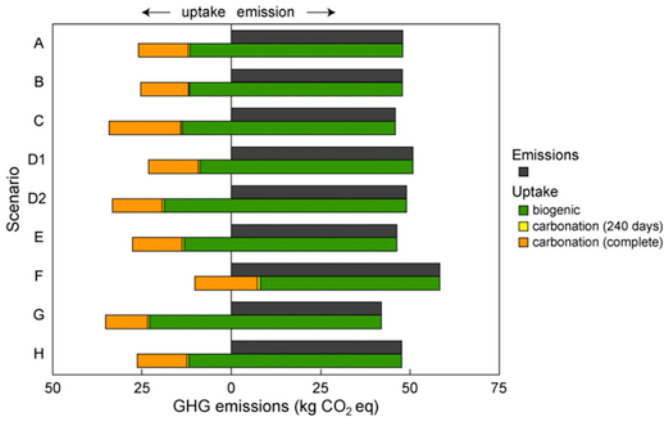

Fig. 6. Greenhouse gas emissions and CO_2 uptake of 1 m^2 of wall made of hempcrete blocks under the different scenarios considered in the sensitivity analysis. CO_2 uptake includes both biogenic uptake and carbonation (after 240 d and at the completion of the process). For each scenario, the bar indicating uptake is aligned to the right end of that indicating emissions; the difference in length between the two bars represents the net greenhouse gas uptake.

bonation. On the contrary, full carbonation would improve substantially the carbon footprint of the hempcrete wall.

7. Discussion

The results of the LCA and of the sensitivity analysis revealed that the main source of environmental impacts of a wall made of hempcrete blocks is the binder production. While the choice of a different binder would reduce some impacts and increase others, a reduction in the amount of binder would in any case guarantee a substantial benefit to the overall wall sustainability. This should be taken into account by lime-based materials producers, who, in most cases, consider lime as a natural and sustainable material. On the other hand, a lower binder-to-hemp mass ratio would generate a block with different physical-chemical properties. The effect of a variation in the binder content on the hygro-thermal and mechanical properties and on the resistance to mould and bacteria needs to be further investigated. Nevertheless, cradle-to-gate emissions would be improved if the base constituents of the block mixture were taken from closer production sites. In this sense, the recent decision of the blocks producer to source hemp from France had detrimental effects on the sustainability of the product. However, a better quality control of the hemp shives produced in Italy could result in a reconsideration of the recent decision.

A comparison of the main outcomes of the present study with those of previous LCA analyses on hempcrete walls published in the primary literature is presented in Table 5. Studies are compared in terms of load-bearing capacity, thickness, coating, construction method, materials density and thermal conductivity (U-value). Although all the considered studies refer to the same unit (1 m^2 of hempcrete wall), the wall systems have several important differences and the associated environmental impacts cannot be directly compared. While, for example, Boutin et al. (2006) considered a non-load-bearing wall, like in the present study, Ip and Miller (2012) and Pretot et al. (2014) considered load-bearing walls and included in the assessment the wooden structure too. Other striking differences among the studies relate to the binder-to-hemp mass ratio, the crop yield production and the binder carbonation. The binder-to-hemp mass ratio depends on the function of the building component assessed and on the preparation mode. In our case, the wall was non-load-bearing and the controlled conditions during production allowed

Table 5
Comparison of published LCA studies on hempcrete walls with the present study. N.A. (Not Available) indicates that the information investigated was not specified in the referred publications. Values of binder carbonation and GHG balance reported for the present study refer to 240 d since blocks production, while the values indicated between parentheses refer to the completion of the carbonation process.

Study		Boutin et al. (2006)	Ip and Miller (2012)	Pretot et al. (2014)	Present study
Functional unit		1 m^2	1 m^2	1 m^2	1 m^2
Wall type		Non-load-bearing wall	Load-bearing wall	Load-bearing wall	Non-load-bearing wall
Thickness wall + coating (in/out)	(mm)	260 + 0/0	300 + 0/0	240 + 10/20	250 + 0/0
Construction method		Spray	Cast between temporary shuttering	Spray	Blocks
Density	(kg/m^3)	330	275	From 390 to 460 (Collet and Pretot, 2014)	330
U-value	(W/(m^2·K))	0.42	0.19	0.36	0.27
Hempcrete					
Binder	(kg)	54.5	50	45	44.5
Hydrated lime	(%)	N.A.	75	75	80
Hydraulic lime	(%)	N.A.	15	15	0
Cement	(%)	N.A.	0	0	20
Other	(%)	N.A.	10	10	0
Hemp shives	(kg)	24.8	30	20.4	31.4
Binder-to-hemp mass ratio	(kg/kg)	2.2	1.7	2.2	1.3
Water	(kg)	37.2	75.0	67.0	58.6
Other materials					
Timber	(kg)	5.5	4.6	20	0
Mortar	(kg)	0	0	0	4.25
Hemp shives production					
Crop yield	(t/ha)	7.75	7.5	8	15
Shives production	(kg shives/kg crop)	0.60	0.52	0.60	0.75
GHG emissions	(kg CO_2 eq/kg shives)	0.254	0.192	N.A.	0.104
CO_2 uptake					
Hemp growth	(kg CO_2 eq/kg shives)	2.105	1.527	1.7	1.84
Binder carbonation	(kg CO_2 eq/kg binder)	0.249	0.571	0.462	0.012 (0.325)
GHG balance	(kg CO_2 eq/FU)	−35.53	−36.08	−1.6	−12.09 (−26.01)

the increase of the amount of hemp in the mixture. The crop yield considered in our study is almost double than that considered in the other studies: the discrepancy may stem from more suitable climatic conditions for hemp cultivation in Italy compared to France and England, or from higher soil productivity. In this respect, it should be reminded that the data used in the present study are those collected directly from the Italian hemp producer (Zampori et al., 2013). Finally, differences in the estimates of CO_2 uptake during the use phase of the material derive from the fact that all previous studies considered a complete carbonation of the wall during its lifetime. Considering a complete carbonation led to very favourable estimates of the GHG balance, but the assumption seems to be unrealistic, as revealed by our measures of the carbonation rate over the first year of life of the product (see section 3.2). The choice of the allocation factors for the co-products of hemp cultivation inevitably affected results. However,

even though an economic allocation would better highlight the benefits of using a by-product, the prices of the co-products vary from year to year, making the physical allocation preferable. Despite some differences in the basic assumptions and the consequent results, all studies highlighted that hempcrete acts as a carbon sink and that its overall carbon balance is negative if CO_2 uptake is included in the analysis.

8. Conclusions

Hempcrete is a natural building material whose use is rapidly spreading across Europe and North America. The hempcrete mixtures are usually prepared directly at the construction site; recently, however, there has been an increasing interest in producing blocks at an industrial scale to be used like traditional bricks. In the present work, a complete environmental assessment of hempcrete blocks was carried out, using the LCA methodology for the first time. The life cycle impact assessment was performed in accordance with the standard for construction materials (CEN, 2012).

Dry hempcrete blocks are a viable alternative to traditional non-load-bearing hempcrete walls, with the additional advantage of reducing substantially the typically long drying time. The environmental impacts of the additional processes inside the blocks' factory gates (i.e. pressing and drying) proved to be negligible compared to the overall impact of the wall, and they are comparable to the energy consumption for mixing the components on site when cast between shutters and to the energy consumed for spraying in the case of sprayed hempcrete. Moreover, the use of dry blocks (slightly wetted during the wall erection due to the use of mortar) avoids the environmental impacts related to the possible use of mechanical drying to reduce construction times.

The high amount of hemp in the mixture allows blocks to store a great quantity of carbon, which is subtracted from the atmosphere through photosynthesis during plant growth and by carbonation during the use phase of the blocks. Considering that the amount of CO_2 stocked in the material was higher than the overall emissions during production, and that the material will continue to store carbon even after the building's end of life, hempcrete blocks can be considered as a carbon sink. The employment of hempcrete blocks could therefore be incentivised by European governments as a strategy to tackle climate change given that, as insulators, they reduce the building energy requirements and, as building materials, they remove more CO_2 from the atmosphere than they emit.

The environmental performances of the material appeared even better when considering the absorption of CO_2 through the carbonation of calcium hydroxide during the wall use phase. However, the common assumption that the wall goes through a complete carbonation during the use phase seems unrealistic: the real rate of carbonation of the material was measured through XRPD, and no carbonation was detected at the inner depths after 240 d. Moreover, the carbonation rate would be further reduced if a covering were applied to the wall. Means to improve the carbonation of the material could be investigated in order to increment the short-term mechanical properties of the material, to reduce the need for cement and, consequently, to improve the life-cycle environmental profile. Finally, to increase the accuracy of the environmental impact assessment of the material, indirect land use changes caused by hemp cultivation should be included in the analysis. When land use is changed from the production of food crops to that of biomasses for other uses, it must be considered that food production displaced by biomass production has to be moved elsewhere (unless demand is assumed to decrease) and could lead to additional environmental impacts such as deforestation and loss of biodiversity. Although these impacts may have a negligible extent as long as hemp-based materials remain restricted to a relatively narrow market niche, more comprehensive assessments will be necessary if their use will spread to a wider market in the future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.02.161.

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