Energy and environmental assessment of industrial hemp for building applications: A review

Carlo Ingrao [a,e,*], Agata Lo Giudice [b], Jacopo Bacenetti [c], Caterina Tricase [a], Giovanni Dotelli [d], Marco Fiala [c], Valentina Siracusa [e], Charles Mbohwa [b]

[a] *Department of Economics, University of Foggia, Largo Papa Giovanni Paolo II, 1, Foggia 71121, Italy*
[b] *Department of Quality and Operations Management, Faculty of Engineering and the Built Environment, University of Johannesburg, APB Campus, PO Box 524, Auckland Park 2006, Johannesburg, South Africa*
[c] *Department of Agricultural and Environmental Sciences, Production, Landscape, Agroenergy, University of Milan, Via G. Celoria 2, Milan 20133, Italy*
[d] *Department of Chemistry, Materials and Chemical Engineering "G.Natta", Politecnico di Milano, INSTM RU-POLIMI, Piazza L. da Vinci, 32, Milan 20133, Italy*
[e] *Department of Industrial Engineering, University of Catania, Viale A. Doria 6, Catania 95125, Italy*

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Abbreviations: AAC, aerated autoclaved concrete; CED, cumulative energy demand; CF, carbon footprint; EPS, expanded polystyrene; EROI, energy returned on investment; EU, European Union; FAOSTAT, Food and Agricultural Organisation of the United Nations—Statistics Division; FRC, fibre reinforced concrete; FU, functional unit; GHG, greenhouse gas; GGP, greenhouse gas protocol; GMT, glass–fibre mat thermoplastics; GWP-100, 100-year global warming potential; HDPE, high density PE; LCA, life cycle assessment; LCCA, life cycle cost analysis; LCEA, life cycle energy analysis; NMT, natural-fibre mat thermoplastics; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; SMB, stabilised mud blocks; WTE, waste-to-energy

* Corresponding author at: Department of Economics, University of Foggia, Largo Papa Giovanni Paolo II, 1, 71121 Foggia, Italy.
E-mail address: carlo.ingrao@unifg.it (C. Ingrao).

1. Introduction

Climate change is increasingly drawing the attention of scientists and policy makers worldwide, thereby becoming a global concern. During the last few decades, the global climate has changed rapidly and will continue to change with time: therefore, interventions are needed to enable global pollution mitigation so as to contribute to preserving the global environment and the planet itself [1]. In this regard, it should be observed that a significant contribution is given by buildings due to consumption of both embodied energy and natural resources as well as to emissions to air, water and soil during all the phases of their life-cycles. According to Dixit et al. [2], the embodied energy (generally expressed as primary energy) represents the energy sequestered in buildings and building materials during all processes of production, on-site construction, and both final demolition and disposal. Direct and indirect energy are the two primary components of the embodied energy: in particular, direct energy is used for construction, operation, renovation, and demolition of a building; whilst, indirect energy is consumed by a building for production of the materials used in its construction and technical installations [1,3]. In addition to the embodied energy, the operational energy should also be considered when intending to assess building life-cycle energy. Based upon the definition provided by Dixit et al. [2], operational energy is the energy expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating building appliances.

According to Sadineni et al. [4], today's buildings are responsible for a significant portion of the energy consumed in the developed countries. Indeed, in many of them building energy consumption accounts for approximately 40% of the whole energy demand, whilst space heating and cooling requires almost 60% of the total energy consumed in buildings [5]. As far as the European context is concerned, buildings account for almost one third (and even more in some specific countries) of the total energy-related emissions of carbon dioxide (CO_2), depending upon the energy consumption fuel mix [6]. Such emissions consist, primarily, of embodied CO_2 as well as of the CO_2 generated during the following phases: material production and building assembly; building operational life (this is directly related to the building energy efficiency and the site-dependent energy generation method applied); and also, building disassembly and subsequent disposal of the component materials [7].

Along time, numbers of researchers have carried out studies aimed at investigating the building sector by assessing the related energy, environmental and economic issues in order to find ways for global sustainability enhancement: in this regard, several reviews have been performed in recent years. For instance, Cabeza et al. [1] carried out a detailed and complete review in order to summarise and organise the literature on Life Cycle Assessment (LCA), Life Cycle Energy Analysis (LCEA) and Life Cycle Cost Analysis (LCCA) studies for estimation of the energy efficiency and of the environmental and economic sustainability related to buildings. Furthermore, with regard to building energy issues, Dutil and Rousse [8] introduced the concept of Energy Returned On Investment (EROI) in buildings as a yardstick to try to shed some light on the claim that the cheapest energy is the one that is not needed. In agreement with Huijbregts et al. [9], they observed that values of estimated EROI in energy saving strategies are high if compared to most of the energy production strategies, thereby highlighting the positive environmental impact of energy conservation. The cheapest energy is the one that is un-used, even though this statement might be questioned in some cases: for example, when an extra-foot of insulation is added on an already well insulated building enveloped. As a matter of fact, it could happen that the benefit in terms of energy conservation is no longer justified based upon the energy used for production, installation and disposal of the insulation system used. In this regard, Kaynakli [5] reviewed numbers of studies in order to estimate the optimum thickness of the thermal insulation material in a building envelope and its effect on energy consumption. The author documented that the optimum insulation thickness and the resulting energy requirements for indoor heating and cooling are strictly dependent upon the number of annual heating and cooling degree-days associated with the climatic zone in which the building is located.

With regard to building materials, Cabeza et al. [10] considered low carbon and low embodied energy materials in buildings, thus highlighting the difficulties found in measuring embodied energy and, also, in comparing published data. However, that study contributed to efforts to develop new materials with less embodied energy. For instance, Gartner [11] discussed the practicality of replacing Portland cements with alternative hydraulic cements in order to allow for lower CO_2 emissions per unit volume of concrete of equivalent performance. According to Reddy [12], stabilised mud blocks (SMB) are energy efficient eco-friendly alternatives to burnt clay bricks since they enable saving around 60–70% of the energy used in burned bricks.

For building insulation materials, Asdrubali et al. [13] presented an updated survey on the acoustical properties of sustainable materials, including mixed and composite ones as well as systems such as green roofs and green walls. The authors highlighted that such materials cause very low impact to human health and to the environment compared to conventional materials and, that the total energy demand for manufacturing and installation is generally low based upon a life-cycle approach that includes also the disposal scenario. Shrestha et al. [14] described a proposed protocol with the aim of providing a comprehensive list of factors to be considered when evaluating the direct and indirect

Nomenclature

CO_2	carbon dioxide
NaOH	sodium hydroxide

environmental impacts associated with building insulating materials' life-cycles, as well as a detailed description of standardised calculation methodologies to determine those impacts. The findings from the study encouraged the use of advanced building insulation materials to provide higher energy savings and lower lifetime environmental impacts. In this regard, Mohanty et al. [15] considered the merits of the critical discussion on natural resource preservation and recycling that is increasingly leading to the renewed interest to biomaterials and, in particular, to renewable raw materials and energy. The study considered bio-fibres (hemp, for instance), biodegradable polymers, and bio-composites giving useful and detailed information on product classification, material properties, economic cost aspects, availability and main applications. More than a decade later, Shazad [16] focussed attention upon hemp supply-chains and products by carrying out a study specifically aimed at providing a complete view of the state-of-the-art on hemp-fibre composites made of thermoplastic, thermoset and biodegradable polymer matrices.

Joshi et al. [17] investigated the field of bio-composites and reviewed selected LCAs in order to compare composites made of natural fibre, such as hemp and China reed, with those made of glass fibre. Doing so allowed the authors to identify the major drivers of the related environmental performance of natural fibre composites, and to draw conclusions about whether the specific findings of those studies can be generalised or not.

Finally, Rehman et al. [18] reviewed the potential of hemp-biomass for bioenergy (bioethanol, biodiesel, biogas, bio-hydrogen) production exploring, also, prospective cultivation in Pakistan in order to meet current and future energy demands.

In the light of the above, it can be concluded that several of the review-studies detected have already investigated both properties and supply-chains of vegetal materials. However, none of them dealt with analysis of their energy and environmental performances by reviewing both aims and findings of the related assessments performed. The study here discussed contributed to this area: it aimed, indeed, at offering an exhaustive survey of studies that have been developed up to February 2015 to address the environmental and the energy issues related to the use of industrial hemp materials for building applications. Standard parameters to be taken into account when intending to perform energy and environmental assessments of hemp-based building materials were also identified by this team of authors.

The study was conducted because the use of natural materials represents one of the pathways to achieve energy efficiency and environmental sustainability in buildings and so it is worthy of attention and analysis. In particular, the research was focussed upon industrial hemp because the latter is acknowledged worldwide as one of the most used vegetal materials in buildings. Therefore, considerations were believed by the authors as desirable to be made based upon the findings of the reviewed papers, in order to identify ways for global improvement and also to enable enrichment of the international discourse in the field.

Finally, for greater understanding, both set-up and development of the study were summarised as shown in Fig. 1.

2. Sustainable materials for building construction

As already highlighted in the previous section, the construction of buildings and roads is responsible for nearly half of the raw materials and energy consumed across the planet: therefore, it has major impacts on the depletion of finite resources and on the emissions of Greenhouse Gases (GHGs) resulting from the combustion of fossil fuels [19,20]. This emphasises upon the imperative need for energy savings in buildings and for adoption of more sustainable behaviours, particularly through reduction of energy consumption and, in turn, of GHG-emission [4,21]. Eco-design and energy efficiency are, indeed, urgent concepts that express the need to search for new building materials and technologies that are environmentally friendly and lead to decreased consumption of materials and energy [22]. For instance, Reddy [12] showed that the use of alternative low-energy building technologies results in about 50% reduction of the embodied energy of a building system. According to Paiva et al. [23], using sustainable materials and technologies would enable more sustainable and affordable construction without compromising the comfort standards and the performance specifications that are required nowadays. For this reason, an increasing interest in ecological values and renewable materials has been recently observed [24,25]. Indeed, conventional materials for building construction are increasingly being replaced with sustainable ones, thus enabling reduction of the impacts coming from the construction industry in terms of primary energy use and of GHG-emissions [26]. According to Benfratello et al. [27], this phenomenon is to be attributed to both the higher possibility of finding these sustainable materials near the utilisation sites and their higher environmental compatibility compared to more sophisticated materials that are usually subjected to chemical alterations or to high energy demanding processes. Asdrubali et al. [13] stated that sustainable materials are those which are usually made from natural or recycled materials and whose production has a low environmental impact, requiring small amounts of both energy and non-renewable resources. In particular, the production of recycled materials is an increasing phenomenon which, according to Lertsutthiwong et al. [28], has to do with the prevention of environmental pollution coming from industrial and agricultural wastes. Management of such wastes has, indeed, become a global concern and one of the biggest problems to be faced. Huge efforts are being made worldwide by all the stakeholders involved to solve this problem through recycling of those wastes, thereby contributing to optimising waste management practices and to avoiding the environmental impacts resulting from waste-to-energy (WTE) treatment or sanitary landfill disposal. Moreover, a significant contribution has been given, over the last few years, by researchers who have assessed building thermal insulation systems (made of waste and recycled materials) for enhancement of their energy and environmental quality. In this context, numbers of papers have been published subsequently in order to deliver results from the research-works conducted in this field such as, for instance, those of Briga-Sá et al. [21], Lertsutthiwong et al. [28], Khedari et al. [29] and Ingrao et al. [30].

In the light of their energy and environmental soundness, both recycled and natural materials are commonly used in the green building sector where selection of construction materials is based upon recyclability and renewability of raw materials, and low consumption of resources in the involved production processes [25]. In particular, Ardente et al. [24] stated that the use of natural materials allows for environmental benefits such as reduction of resource consumption; low levels of embodied energy, reduced GHG-emissions; and recovery, re-use, and recycling of the products before the final disposal. Additionally, natural materials can be considered as eco-friendly, since they cause no release in the environment of toxic substances that affect human health and the environment [27,31].

Finally, it should be observed that natural materials can be of animal origin, such as sheep wool, and of vegetal origin, thus

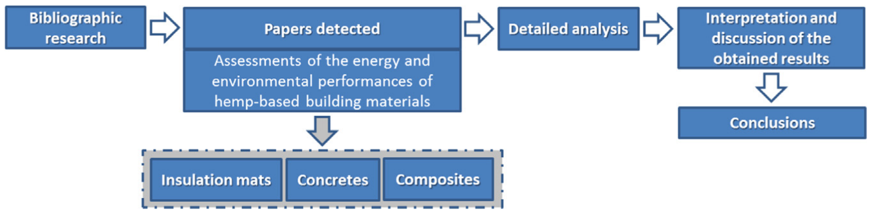

Fig. 1. Study set-up framework[1].

including, in the latter case, hemp, straw, kenaf, flax, wood, and bamboo, which are currently available in the market and usable for several applications [13,30]. In this context, to enable greater understanding of the topic addressed in this research, the next section was dedicated to discussion of the main features and properties of hemp as a multiuse and multifunctional crop usable in a considerable number of industry sectors and, in particular, in buildings.

3. Hemp: A multiuse, multifunctional crop for industrial applications

3.1. Agronomic aspects

3.1.1. Botany and biology

Cannabis sativa L. is an annual C3 herbaceous plant in the Cannabis genus, a species of the Cannabaceae family and was, first, classified by Carolus Linnaeus in 1753. The Cannabis genus is now distributed worldwide from the equator to about 60°N latitude and throughout much of the southern hemisphere [32]. Hemp is believed to have originated in Central Asia, though several researchers advocate for two centres of diversity, namely Hindustani and European–Siberian [33]. It is an annual dicotyledonous angiosperm plant whose stem consists of different morphological regions. The innermost layer is the pith, surrounded by woody material known as hurds (or shives). The outside part of this layer is the growing tissue which develops into the aforementioned hurds on the inside and into the bast fibres on the outside (Fig. 2).

The stem is more or less branched, depending on the crop density. The leaves are of a palmate type and each leaf has 7 to 11 leaflets, with serrated edges; the strong tap-root penetrates deep into the soil. The seed is an achene, grey and green with ovoid shape (3–5 mm long, 2–3 mm wide): the weight of 1000 seeds varies between 20 and 25 g. High yields of good quality fibres are possible throughout Europe. In this context, van der Werf and Turunen [34] highlighted that yield and quality of fibre are affected by density and self-thinning, whilst García-Tejero et al. [35] in Mediterranean semi-arid environment identified irrigation and plant density as the main factors affecting hemp fibre quality. Plant density should be high and prevention excessive lodging and development of fungal infection must be ensured. Maturity class and photoperiodic response of the cultivars are important aspects to be taken into account and, therefore, more research on ideotyping and a wider breeding effort are recommended.

3.1.2. Main physiological features

The hemp plant can grow up to 4 m in some months, with low fertiliser and irrigation demand, making it very efficient in the use of material resources [36]. In this regard, to obtain high production yields and good quality crops, heterogeneity, photoperiod and morphological aspects of the bark require special attention in breeding and crop cultivation compared to other physiological features.

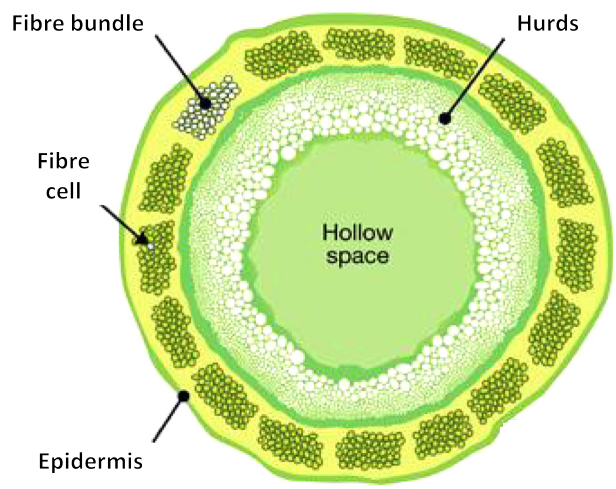

Fig. 2. Hemp stem cross-section[2].

(a) **Heterogeneity**. Hemp is characterised by sexual dimorphism, thereby involving high heterogeneity in the crops [37]. When it comes to the rate of growth and development, strong differences can be observed between male and female plants: for instance, the first tends to flower and senesce earlier [38] and shows higher quality of primary fibres. Moreover, also among plants with the same sex, the competition for light, nutrients and water involve a considerable plant-to-plant variation and may even result in self-thinning [37]. This competition may limit yields, reduce the efficiency of resource use resulting in variable quality.
(b) **Photoperiod**. Hemp is a short day plant. In southern Europe, genotypes should be selected with a longer critical photoperiod to profit optimally from the available growing season [39]. The cultivars that are grown in Europe are usually of French origin and have a critical photoperiod between 14 and 15.5 h.
(c) **Aspect of bark**. Hemp stems can be divided into: (1) 'bark' or 'bast' section, corresponding to the tissue located in the outer part of the stem outside the vascular cambium, (2) the 'woody core' which is located inside the ring of vascular cambium and consists of lignin rich xylem tissue. Both the primary (elementary fibre about 20 mm to 50 mm long) and secondary bast fibres (about 2 mm long) are derived from the vascular bundles in the bark, whereas the core fibres are located inside of the vascular

[1] Personal elaboration.

[2] Extrapolated from "Natural fibres help build green economy", National Research Council of Canada, 2009. Available at: http://www.nrc-cnrc.gc.ca/eng/achievements/highlights/2009/natural_fibres.html [accessed: 12–17–2014].

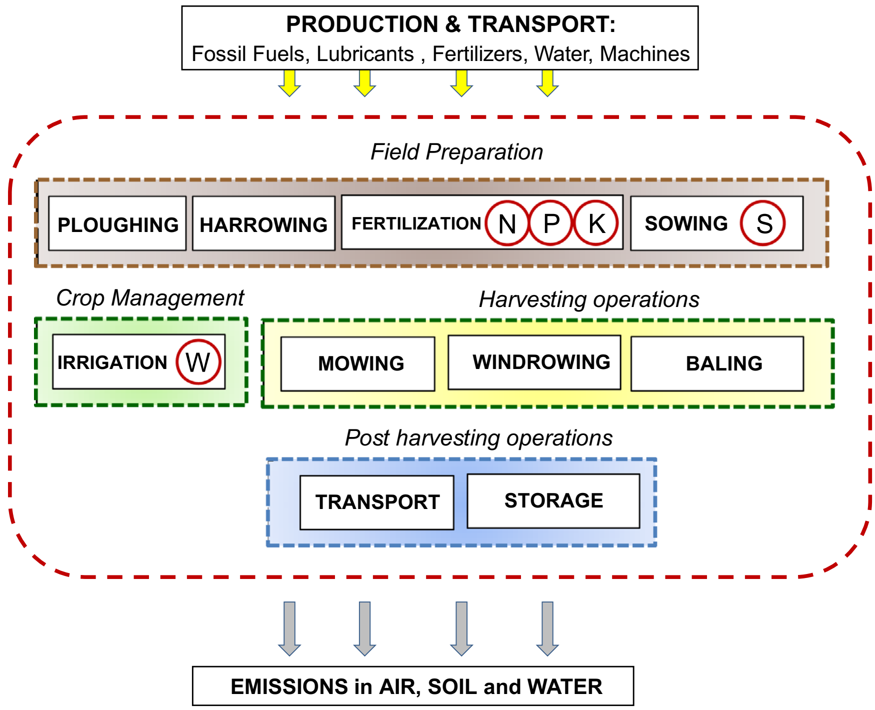

Fig. 3. Main agricultural activities involved in hemp cultivation (see footnote 1).

cambium in the woody core (0.5–0.6 mm long). The primary bast fibres are made up of bundles of pericyclic elementary fibres that are characterised by thick and lignified cell walls.

3.1.3. Cultivation practices

Hemp (*C. sativa* L.) has excellent agronomic characteristics: for instance, it is a slender and annual herbaceous crop which, depending on its handling and agro-chemical aspects, can supply a high yield of dry matter per ha. Fibre hemp may yield up to 25 t above ground dry matter per ha (20 t stem dry matter per ha) which may contain maximum 12 t/ha of cellulose, depending on climate and environmental conditions as well as on the cultivation practices performed and on the genetics (e.g. varieties) [38,40]. High yield variability is observed, for example, in Northern Italy where dry matter yields ranged from 8.3 to 18.7 t/ha over the years and in different locations [41]. Generally cellulose production is 7–10 t/ha [42]. The yield of the dry bast fibre varies from 1.2 to 3.0 t/ha, and seed yield from 0.7 to 1.8 t/ha. Hemp is a spring crop with 120–150 days cropping cycle and can also be an excellent predecessor in crop rotation in particular before winter cereals such as wheat. The establishment of hemp crop involves a good seedbed preparation generally obtained by means of a combination of plough (depth: 30–35 cm) and rotary harrow (1–2 passes on medium texture soil). Fertilisation is carried out before the seeding using both chemical and organic fertilisers such as, in the latter case, animal sewage and manure.

In Southern Europe, sowing is performed in late April, whilst in the Central and Northern Europe this takes place later, until early May. The operation can be carried out using a seed drill (15–20 cm between rows and 1–2 cm deep), as done for winter cereals. Sowing can also be performed by direct drilling in areas with good water availability increasing the seeds rate; nevertheless considering the cost of seed (5.5–6.5 €/kg) this practice is still unusual. Struik et al. [38] highlighted that the relation among plant density and dry matter yield is not significant: It is only with extremely high or low plant density that some sort of effect on the dry matter yield can be observed. After sowing, hemp cultivation is not difficult: the crop requires only rarely the use of plant protection products; also, the weed control does not usually involve the application of herbicide because the crop itself suppresses weeds efficiently [34,43]. Hemp requires low fertilisation: Struik et al. [38] highlighted, very little response of the plant to nitrogen fertilisation in South Europe (Italy).

The mechanisation of hemp harvesting strongly depends on the cultivation purpose. Harvesting is carried out using machines for haymaking [44]. The main field operations for hemp cultivation in Southern Europe were depicted in Fig. 3.

3.2. Fibre, hurds and seeds: Production data and main industrial applications

Hemp is a versatile crop with a vast field of possible uses: for centuries, it has been a source of fibre and oilseed used worldwide to produce a variety of industrial and consumers' products. The global market for industrial hemp, which refers to cannabis varieties as characterised by plants that are low in delta-9 tetrahydrocannabinol (marijuana's primary psychoactive chemical) is high and this is for more than 25,000 hemp products. In this context, Fig. 4 shows a summary of the obtainable products and of the possible uses of hemp.

In the light of the final products' quality requirements, the production process differs considerably in terms of cultivation technique and related unit costs. Harvesting practices differ depending upon non-textile grade fibre, textile grade fibre, or dual purpose and seeds. The operations of cutting and collection of fibre can be divided in longitudinal harvesting, for obtaining long

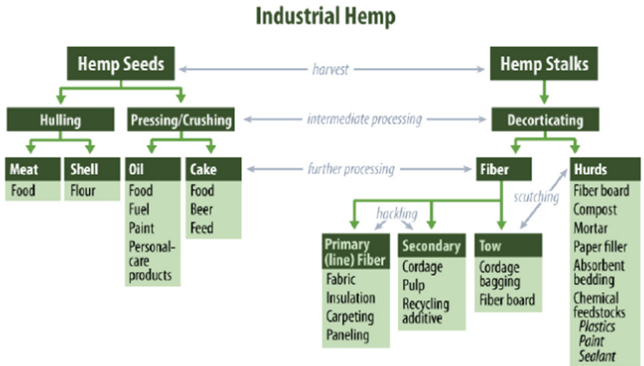

Fig. 4. Hemp products and uses flowchart[3].

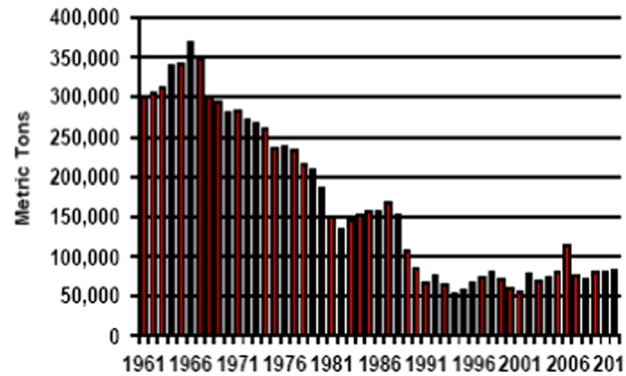

Fig. 5. Global production of fibre (1961–2011).

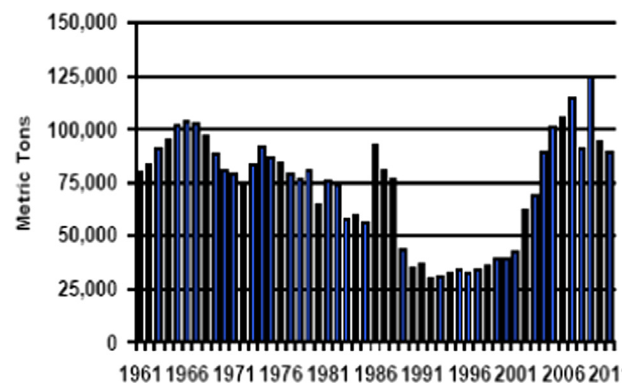

Fig. 6. Global production of seeds (1961–2011).

fibres for textile fine production, and disordered harvesting for obtaining short fibres for technical uses.

For high quality textile-production: plants are grown up to four meters, stalks are maintained in bundles during collection; and, finally maceration of plants in water and extraction of fibres occur. On the contrary, in the case of low quality production, plants are harvested in traditional or round bales and then fibres are extracted via mechanical and physical–chemical treatments without soaking plants in water. Retting is a phase occurring through the combined action of bacteria and weathering. It allows the degradation of the stem material (mainly pectin) surrounding the fibre bundles and allows for efficient processing of fibre. In this context, it should be observed that the following two methods are currently available for use:

- Dew retting: the harvested stalks are windrowed in the field, where the combined action of bacteria, sun, air, and dew causes fermentation, dissolving much of the stem material that surrounds the fibre. Within two to three weeks, depending upon climatic conditions, the fibre can be separated. Dew-retted fibre is generally darker in colour and of poorer quality than water retted fibre.
- Water retting: bundles of stalks are submerged in water which penetrates to the central stalk portion, swells the inner cells, bursting the outermost layer, thus increasing absorption of both moisture and decay-producing bacteria. The stalk bundles are weighted down, usually with stones or wood, for about 8 to 14 days, depending upon water temperature and mineral content [45].

After retting, the separation of the bast fibre is carried out through scrutching (breaking the woody core of the stems into short pieces) and decortication (the separation of bast fibre from the hurds) using specialised machineries. The amount of fibre contained in the stem is approximately 30%, of which 20% is suitable for weaving (long fibres) and 8–10% (short fibres) for the manufacture of paper. Hemp fibres are used in a wide range of textiles and non-textile products, including paper, carpeting, home furnishings, construction and insulation materials. They can be mixed with cement to lighten the weight of cement conglomerates and so used for production of coating materials, auto parts, and composites. Furthermore, they can be utilised also as animal bedding, raw material input, low-quality papers, and composites [46,47].

Hemp for oilseed production is typically grown sparsely in order to promote branching and, therefore, seed formation: in most cases, hemp seeds are a by-product of hemp grown for fibres. Hemp seed is a small nut ovoid, with shiny surface uneven colour from brown to olive-coloured; depending upon the variety, the weight of one thousand seeds ranges from 20 to 23 g. Hemp seeds/grains are smooth and about one-eighth to one-fourth of an inch long. Processing hemp seed involves hulling or pressing and crushing, depending upon the desired output [48]. Hemp seeds are mostly used for stock feed and, to a lesser extent, for oil. They can be used, directly, as a food ingredient, crushed for oil and meal and also in bird seed mixtures. Hemp seed and oilcake are used in a range of new foods products including pasta, tortilla chips, salad dressings, snack products and frozen desserts and non-dairy hemp "milk" beverages with a high level of omega-3 essential fatty acids, and can be an alternative food protein source. Oil from the crushed hemp seed is an ingredient in a range of nutraceuticals and health care products and nutritional supplements. Hemp seed can be used for industrial oils (paint, ink, lubricating oil and sealant), cosmetics and personal care, and pharmaceuticals, among other composites. Finally, it should be observed that industrial hemp suffered a decline until the years 1980s. In this context, Figs. 5 and 6 show trends in the production of fibres and seeds from 1961 to 2011 (most updated data) where an increase in the production of both seeds and fibres can be observed in recent years due to the renewed interest in using them for a series of applications [49].

All that stated, the following section is dedicated to discussing the merits of the main properties of hemp fibres and the use of hurds in the construction industry.

3.3. Use of fibres and hurds in the building construction industry: Analysis of the material properties

As already indicated in Section 2.1, hemp stem consists of a woody core surrounded by an outer skin containing long and

[3] Extrapolated from "Hemp as an agricultural commodity". Available at: http://www.hotstockmarket.com/t/278230/hemp-as-an-agricultural-commodity [accessed: 12-21-2014].

Table 1
Summary of mechanical properties of hemp fibre/hurd lime/cement composites[5].

Composition	Compressive strength [MPa]	Flexural strength [MPa]	Elastic modulus E [GPa]/G[GPa]	Flexural toughness [kJ/m^2]	Specific fracture energy [N/m]
Hemp fibre reinforced concrete					
Aggregates (7–20 mm), sand, cement, fibre (0.18–1.06 wt%, length 10–30 mm)	14–35	3–5		0.7–1.5	
Aggregates (max size 10 mm), sand, cement, fibre (0.19 wt%, length 40 mm)	34.6	3.59		–	204.37
Aggregates (7–20 mm), sand, cement, fibre (0.5–1.0 wt%, length 30 mm)	17–20	2.2–3.0			
Hemp—cement paste					
Cement, pre-cut hemp fibre (1 mm–1 cm), fibre pre-treatment in alkali environment	–	6.8–9.5	12.7–13.1 /5.1–5.3		
Cement, hemp material (fibre 35%, hurd 62% and dust 4%)	0.55		0.049		
Hemp—cement mortar					
Cement, sand, fibre (1.1–3.1 wt%; length 2–3 cm), carbon nanotubes (0.01–0.06 wt%)	31.5–43	10.8–12			
Lime–Hemp Concrete (*LHC*)					
Hydrated lime, hydraulic lime, hemp material (fibre 35%, hurd 62% and dust 4%)	0.15–0.20		0.013		
Hydrated lime, hydraulic lime, cement, hemp material (fibre 35%, hurd 62% and dust 4%)	0.44–0.83		0.017–0.028		
Hydrated lime—hydraulic lime (4:1), hemp hurd (2–8 mm; < 40 wt%)	0.044–0.462	0.080–0.141	0.007–0.040		
Hemp—gypsum plaster					
Gypsum, fibre (length 1 mm–1 cm), fibre pre-treatment in alkali		2.8–3.8	2.4–2.8/1.0–1.1		

strong fibres. Hemp stems processing produces two materials: hurds and fibres. Hemp fibres are the most valuable part of the plant, and in the building industry they are usually used as insulation. Fibre Reinforced Concrete (FRC), a composite concrete material consisting of a hydraulic cement matrix reinforced with discontinuous discrete fibres dates back to 1960s [50]. Originally, synthetic fibres, (metal or glass) fibres were used but, as already largely documented in this paper, in recent years the interest in greener building materials has led to the investigation of natural fibres in order to replace synthetic ones. However, despite their advantages as reinforcing materials in concrete [51], they are still not fully explored. On the other hand, hemp hurds are extensively used in hemp lime products. Hemp lime composites have been used in France throughout the 1990s and now there are many examples of hemp lime constructions in other countries [20]. Hemp lime composites, often referred as hemp concrete or simply "hempcrete", are building materials formed from a mixture of hemp hurds as aggregate and lime based binders: they find applications in wall, floor and roof insulation. A novel organic–inorganic binder has been recently suggested in hemp hurds composites [52].

Recent literature on hemp fibre reinforced concrete and hemp hurds composite demonstrates that mechanical properties of these composites have been tested on lab-scale specimens for compressive strength, flexural strength, and flexural toughness. The mechanical properties have been found to strongly depend upon both binders used and fillers and aggregates added. Lab tests were run on hemp fibre/hurd composites with different binders, both hydraulic and non-hydraulic: cement [31,50,53–58], gypsum plaster [59], hydrated lime [27,54,60], hydraulic lime [27,54,61,62], mixtures of hydraulic and non-hydraulic lime [26,62–64], lime-based binder without additional specifications [20,65–67]. In some studies, hemp fibres and hurds only partially substitute aggregates and sand [50,55–58,60]. Occasionally, hemp fabric [31,57,68] or hemp fibre grids [69] are used. A summary of the mechanical properties of the hemp fibre/hurds lime/cement composites was reported in Table 1. Ranges of values correspond to composites with the same qualitative composition but different quantitative amounts of ingredients. In some cases, differences arise from specific fibre treatments. For greater understanding of the table, it is underscored that standard deviations are not included in the table.

Polymer composites reinforced with hemp fibres have only recently attracted the interest of researchers with the aim of producing high-performance polymer-based materials with specific mechanical properties [70,71]. However, not all recent reviews in the field give an account of hemp fibre reinforced polymer hybrid composites [72]. Recent studies in this area have been done on polypropylene–hemp fibre composites, manufactured using a specific processing cycle, trying to respect the integrity of the fibres during manufacturing [73]. In this study, the author documented improvements in Young's modulus (1.9 GPa), but a slight decrease in ultimate strength (19 MPa) with respect to pristine PP. Other examples of studies of PP composites exist [71] and another study considered the composites with hemp fibres embedded in an epoxy-matrix specifically tested for acoustical applications [74].

Finally, it should be underscored that recently there has been an upsurge of interest in thermal and hygrothermal properties as well as in the environmental compatibility of hemp based building materials: this was discussed in the next section.

4. Environmental sustainability and energy efficiency of hemp-based materials for building applications: A review of assessment cases

As shown in the previous section, the physical–chemical and mechanical properties of hemp make it a good candidate for use in series of industrial sectors, in the form of fibres and hurds. In buildings, these two hemp products are used for production of insulation mats, concretes and bio-composites. Detailed evaluation of the energy and environmental performances of these building

[5] Personal elaboration from papers reported in Section 3.3.

materials was performed in this section by analysing both objectives and findings of the studies discussed in the papers reviewed. Once collected, the latter were selected based upon the relatedness to the objectives of the present review, thus contributing to valuable results and considerations.

4.1. Thermo-acoustic insulating mats

One of the most widespread ways to use hemp fibres is to manufacture mats to be employed in buildings with thermo-acoustic insulation functions. A considerable number of authors have worked on the assessment of both energy and environmental performances of these products. For instance, Zampori et al. [75] performed an LCA of the production (technical fibre and woody core) and use of hemp for the evaluation of the impact generated by the manufacturing of a hemp mat with a thermal conductivity of 0.044 W/m K. The study included assessment of the inventory flows and environmental burdens associated with the cultivation of 1 ha of land and of the sustainability of two walls, where the insulating performances were guaranteed alternatively by hemp-based or rock-wool insulating panels. The authors used mass allocation considering that, as also clarified in the previous sections, hemp cultivation delivers the following three co-products: woody core; fibre; and, dust. According to the authors, 1 t of dried hemp yields 70% for the woody fraction, to 25% fibres and up to 5% dust particles. Therefore, it can be said that fibres are responsible for 25% of the damage due to cultivation of 1 ha of hemp land: this aspect was considered by the authors for implementation of the panel production and, in turn, of the life-cycle of the walls. Interestingly, the following three indicators were used by the authors for assessing the environmental burdens associated with the production of hemp (in the amount required for mat manufacturing) and with the two designed walls: Greenhouse Gas Protocol (GGP); Cumulative Energy Demand (CED); and, Ecoindicator99. The study highlighted that, for all the aforementioned impact indicators, hemp fibre production is the most impacting process in the production of the manufactured panel and, in turn, of the life-cycle of the designed walls. In this regard, the authors documented that the highest contribution in terms of 100-year Global Warming Potential (GWP-100) comes from the fertilisation phase in terms of both production and management of the fertilisers required. From CED calculation, hemp usage resulted in more renewable energy. Moreover, from application of the Ecoindicator99 method it appeared that hemp fibre production affects the non-renewable energy resource stock due to the high consumptions of fossil fuels associated with the agricultural activities involved and to the retrieval and transportation of all the input materials required. This aspect was also stressed by Fassi and Maina [76] who evidenced that, in terms of primary energy, hemp fibre with a total energy consumption of 15 MJ/kg uses less energy than mineral and synthetic materials, but more energy than other natural materials. This aspect is mostly related to the phases of input material production and supply that represent almost 64% of the aforementioned value, with a total consumption of primary energy equal to 9.63 MJ/kg.

These environmental aspects had already been highlighted by van der Werf [77] who conducted LCA to compare the environmental impacts of cultivation of hemp to those of the cultivation of other annual crops, such as sunflower, pea, wheat and maize. This study showed that hemp is one of the less harmful crops with highly reduced impacts when it comes to eutrophication, climate change and energy use, hence recommended for building applications. Zampori et al. [75] made the same consideration and in addition, concluded that hemp-fibre mats are valid alternatives to conventional materials and are feasible for application in the green-building sector. A comparison performed by the authors between a hemp and a rock-wool mat showed, indeed, that the former is far less impacting than the second. This was attributed to the CO_2-uptake associated with hemp-plant photosynthesis, thereby enabling GWP-100 credits that offset the GWP-100 burdens of the mat production. Suitability of hemp fibres for building uses (i.e. for thermal insulation) had also been pointed out five years before by Kymäläinen and Sjöberg [25] and attributed also to fibre biodegradability which enables reduction of the environmental impact at the end-of-life phase. However, the two researchers showed that such fibres have a risk for microbial and other contaminants and, so, it is recommended that their quality is monitored regularly. Furthermore, harvesting, processing, manufacturing, building construction, and maintenance should be carefully executed in order to avoid the risk of negative effects (i.e. moulding) caused by moisture and free water. Finally, product development of fibrous thermal insulations and the use of additives are evidently needed in order to avoid negative effects on indoor air quality [25].

Another interesting comparison was carried out by Menconi and Grohmann [78] who developed a thermal simulation model integrated in an LCCA-based approach aimed at identifying the best choice of insulating material to retrofit the roofs of an extensive sheep farm building. The study showed that all of the considered insulating materials work well for increasing the period of time in which a temperature of comfort is maintained so as not to exceed the critical value for animal welfare. By analysing their entire life-cycles, the best materials were found to be glass wool, sheep wool, and hemp fibre, whilst the polyurethane ranked last because of its high primary energy input though it presents the best response in terms of temperature control. Hemp fibre was confirmed to be one of the less energy demanding and GHG emitting materials. Fassi and Maina [76] also found out that, compared to other natural materials and, most of all, to conventional materials of mineral and synthetic origin, hemp fibres cause slight impacts in terms of consumption of non-renewable resources and energy for production and processing and, also, for disposal at the end-of-life. In contrast, they documented that hemp fibres cause no impacts on ozone-layer depletion, greenhouse effect and acidification.

Finally, Korjenic et al. [79] proposed the use of hemp, jute, and flax fibres for developing new insulating materials with physical, mechanical, and insulating properties comparable to those of the commonly used building insulation materials. The findings of the study showed that, for the considered six samples, thermal conductivity increases from an average value of nearly 0.044 W/m K to an average value of almost 0.057 W/m K with a moisture content between 0 and 14%. Furthermore, it was observed that, depending upon the samples' moisture percentage and composition, very low values of thermal conductivity can be obtained, thereby increasing competitiveness of these materials with respect to the conventional ones. It was also observed that when the moisture content is less than 10% and the content of hemp fibres and hurds is between 48 and 64% and between 16 and 32%, respectively, with a bi-component fibre content of 20%, thermal conductivity levels out at between 0.039 and 0.044 W/m K. Thermal conductivity of expanded polystyrene (EPS) panels usually settles at between 0.030 and 0.040 W/m K based upon its density. The use of hemp fibre mats enables comparable thermal insulation performances with much higher levels of environmental compatibility. In conclusion, it can be asserted that all the authors of the detected papers pointed out that hemp-fibre mats represent a valid alternative to conventional materials used for building thermo-acoustic insulation thanks to their energy and environmental performance. However, their intrinsic quality should be continuously kept under control so as to assure indoor air quality and comfort conditions and, as a result, to avoid that hemp fibre materials represent a risk for human health.

4.2. Composites

Two of the authors who worked first in the field of hemp composites were Pervaiz and Sain [80]. They investigated mechanical properties and environmental performance of mat thermoplastics made of finished natural fibre (NMT) and compared the obtained results with mat thermoplastics made of glass fibre (GMT). The performed analysis highlighted that natural fibres, such as hemp, have great potential to act as sustainable 'sink' for CO_2 and that their use enables saving of non-renewable energy resources. For this reason, hemp fibres should be preferred to the glass ones thus allowing more eco-friendly composites to be produced. The environmental benefits of hemp fibre for production of bio-composites were further highlighted by many authors who tested the use of hemp fibre as reinforcement for production of composites made of several polymer materials, such as, polypropylene (PP) and polyethylene (PE). Bourmaud et al. [81] conducted a study with the aim of environmentally exploring the changes of the main characteristics of a recycled PP/hemp composite produced using PP coming from various industrial wastes after multiple injection mouldings. The assessment highlighted an overall reduction of the estimated impacts for acidification and for non-renewable energy consumption mainly. This emphasises upon the environmental feasibility of using a recycled matrix to bond hemp fibres in order to produce polymer/vegetal fibre compounds. The addition of hemp fibre to composites made of High Density PE (HDPE) was tested by Lu and Oza [82]. They investigated the effect of silane and sodium hydroxide (NaOH) treatment of hemp fibres on the thermal and thermo-mechanical properties of composites produced by adding hemp fibres to the HDPE matrix.

A different polymeric paste was considered by La Rosa et al. [22,83] who tested both environmental and economic cost of a hybrid composite produced by hand lay-up of glass woven fabrics and natural fibre mats with an epoxy vinyl ester resin. They concluded that the use of hemp mats in glass–fibre reinforced thermosets allows for increased environmental sustainability and increased economic convenience compared to conventional glass–fibre alternatives. Finally, some studies have recently dealt with using hemp hurds for production of composites which, as indicated by Arnaud and Gourlay [62], can be used as filling material of a load-bearing structure with thermal and acoustic insulation function. Sassoni et al. [52] presented novel hemp-based composite materials, in the form of panels, produced by bonding hemp hurds with a new hybrid organic–inorganic binder, made of magnesium oxide and a reactive vegetable protein in the form of flour. Three different levels of density (low, medium and high) depending upon the dimensions of the coarse hemp hurds were considered for production of the samples to be tested. The obtained results highlighted that low-density panels are most suitable for building thermal insulation with a thermal conductivity value of 0.078 W/m K which increases to 0.138 W/m K in the case of the medium-density panels. On the contrary, high-density panels showed no significant contribution to thermal insulation, since they were designed for providing good resistance levels against physical and mechanical stress. It is clear that the lower the thermal conductivity is the more energy and environmental sound the building is, thereby making these composites very promising new materials for buildings.

4.3. Concretes

Hemp hurds can be utilised for the production of concrete, known as "hemp concrete or hempcrete", a bio-aggregate based material in which hemp hurds are pasted together with lime-based binders [84]. It should be observed that, whilst concrete made of hemp hurds is used for its thermal insulating properties and not for bearing loads, the possible exploitation of hemp-fibre tensile strength has been recently investigated with the aim of producing FRCs [58]. Hemp concrete is generally suitable to form building envelopes by casting between, or spraying against, temporary or permanent shuttering in situ, or by pre-fabrication of building blocks or panels [85]. This material is being increasingly recommended by eco-builders because of its low environmental impact associated with the use of a renewable raw material (hemp). Moreover, being vegetal, it enables carbon sequestration during plant growth [86,87]. As previously clarified, it is characterised by very good thermo-acoustic properties and, also, by good levels of transpirability and hygroscopicity that make it a good regulator of the indoor moisture content, so contributing to better indoor air quality [88]. Stevulova et al. [86] tested the thermal conductivity of hardened concrete made of chemically modified dried hemp-hurds bonded with caustic-magnesite based cement. They measured values of thermal conductivity between 0.068 and 0.123 W/m K depending upon the samples' density, thus found to be comparable with the values related to alternative conventional building-materials, such as aerated autoclaved concrete (AAC). For this reason, the authors stressed that hemp concrete should be preferred to conventional ones of equal functionality and thermal conductivity. Maalouf et al. [31] presented some preliminary investigations on the transient hygro-thermal behaviour of a hemp concrete envelope under summer conditions in France. The study was divided into two parts: the first was related to comparison of the thermo-physical properties of hemp concrete to those of other materials used in construction, whilst the second investigated the material hygro-thermal behaviour in a building envelope. A coupled heat and mass transfer model was implemented by that team of authors and, then, validated with experimental data. It was concluded that in Southern France, there is a risk of indoor superheating for more than 70% of the occupation period, due to the low effusivity of hemp concrete. This problem is believed to be common in most Mediterranean countries where summer conditions are quite challenging and, therefore, improvement solutions are needed to be identified and evaluated, for indoor superheating mitigation. It is proposed to use the combined effect of external solar shading, night ventilation technique and high energy storage capacity materials for improving indoor quality and comfort. Such a solution may be insufficient in South France and, so, coupling hemp concrete with a higher thermal inertia component could be desirable. However, this result cannot be generalised to other countries because the building envelope must fit several insulation characteristics imposed by each country's regulations. For this reason, different wall thickness or configurations should be considered for building energy efficiency improvement.

Shea et al. [85] investigated the hygro-thermal performance of an experimental hemp–lime building and compared the results of steady-state co-heating tests with laboratory tests and computer simulations of transient performance. The authors showed that the test-building envelope provides significant rates of attenuation of the oscillations in the external environment which will assist in maintaining comfortable summertime conditions within the building, whilst reducing energy requirements for heating and cooling. Collet and Pretot [84] found out that the thermal conductivity of hemp concrete depends upon its formulation, density, and water content. In particular, it was noted that the water content has a lower effect than density on thermal conductivity which increases and levels out at 15–20% on the basis of the relative humidity. This effect should be taken into account in the modelling process of a building-envelope's hygro-thermal behaviour in order to increase energy efficiency of buildings and, in turn, their environmental performance.

The moisture and thermal properties of hemp concrete were assessed by Walker and Pavía [26] who investigated the effect of the type of binder on the moisture transfer and on the thermal properties of hemp–lime concrete. This was done by comparing concretes made of hydrated lime and pozzolans with those made of hydraulic lime and cement. Based upon their findings, the authors concluded that the type of binder influences the capillary absorption of hemp concrete, and that both increasing the hydraulicity of the binder and adding a water retainer reduce capillary absorption. This is probably due to hydrates filling micro-pores in the binder. On the contrary, the binder type appeared not to have a significant effect on both thermal conductivity and specific heat capacity. Nonetheless, current trends suggest that binder hydraulicity reduces thermal conductivity and, at the same time, increases heat capacity, whilst the presence of water retainers appears to have an increase effect on the aforementioned thermal properties [26].

Over the years, there have been researchers that have assessed mechanical and thermal properties of hemp concrete: for example, Elfordy et al. [89] and Nguyen et al. [64]. The first group of authors dealt with concrete blocks made of a mixture of lime and hemp hurds and manufactured by a projection process. They investigated the influence of the projection distance on the homogeneity and density of these blocks, as well as the influence of material density on energy and mechanical performance. The findings of this study showed that the thermal conductivity of the analysed blocks increases (from 0.179 W/m K to 0.485 W/m K) with the increase of their density and, in turn, of their hardness. This aspect is of relevance because it emphasises that these blocks can have different functions depending upon the intended use: this aspect has to be taken into account, for the correct design and construction of buildings. By way of example, lightweight blocks can be used and, therefore, low values of density and thermal conductivity attained. In contrast, when these blocks contribute to construction' structural integrity, high values of density and hardness are needed. This increases thermal conductivity and reduces thermal insulation capacity. It is clear that, in this case, an additional insulation layer would be desirable to enhance thermal insulation capacity of the building envelope and better energy efficiency. However, it is possible to achieve a compromise between thermal insulation and mechanical properties as a function of the type of construction desired.

Some studies showed that optimisation of precast elements (bricks or hollow blocks) made of a mixture of lime and hemp can be achieved through compaction of fresh material during casting. Doing so would enable increased mechanical strength of the concrete, whilst reducing the amount of binder needed. This concrete can be used for producing precast load-bearing elements which have good levels of thermal insulation. In this context, Nguyen et al. [64] highlighted the fact that the compaction process on one side enables increasing resistance to mechanical stress and on the other side, due to reduction in the volume of the air entrapped within the voids, leads to reduction of thermal conductivity. The findings of that study are in agreement with Elfordy's et al. and reinforce the importance of the correct definition of the function that these precast elements are expected to fulfil within a building structure.

Many studies have demonstrated that the use phase is the most environmentally harmful in buildings' life-cycles, mainly due to the scarce thermal insulation of the envelope which leads to increased consumption of the energy required for indoor heating and cooling. Therefore, in order to contribute to reduction of the environmental impact of buildings, it is first highly recommended to reduce the thermal fluxes through the envelope, thus allowing enhancement of building energy efficiency [87]. This can be achieved by equipping the envelope itself with highly insulating eco-friendly materials and, also, by installing glazing-equipped windows, increasing thermal insulation, energy efficiency and environmental sustainability. In this regard, Pretot et al. [87] performed an LCA of a sprayed hemp concrete wall which included concrete, wood frame, and rendering. A "from-cradle-to-grave" approach was used, considering a 100-year life span of the wall, including the following phases: hemp-hurd production from hemp cultivation as well as both binder and wood-framework production; and wall construction, use, and end-of-life. The authors found out that the raw material production is the most impacting phase, mainly due to highly negative contribution coming from production of the required amount of binder to be used. The balance of the climate change indicator was favourable as CO_2 uptake by the photosynthesis occurring during the plant growth considered for the hemp cultivation process carbonation is higher than emissions: this result agrees with Zampori et al. [75]. The same was noted by Ip and Miller [20] who performed a Carbon Footprint (CF) study with the aim of establishing the life-cycle GHG-emissions associated with the construction of 1 m^2 [functional unit (FU) chosen] of a hemp–lime wall in the UK with a lifetime horizon of 100 years. It was noted that a hemp–lime wall of 1 m^2 and 0.3 m thick without any wall finishes can sequestrate 82.71 $kgCO_{2eq}$. This not only compensates 46.43 $kgCO_{2eq}$ of GHGs emitted in the growing and manufacturing processes but also enables storage of 36.08 $kgCO_{2eq}$. A similar result was obtained by Walker and Pavía [26], namely that 1 m^2 of hemp–lime wall (260 mm thick) requires 370–394 MJ of energy for production and sequesters 14–35 $kgCO_{2eq}$ over its 100 year life span compared to an equivalent cellular Portland-cement concrete wall that needs 560 MJ of energy for production and releases 52.3 $kgCO_{2eq}$. In this regard, Ip and Miller [20] stated that the positive impact in terms of carbon sequestration is even more significant when taking into account the displacement of GHG-emissions, which would otherwise have been created if another type of conventional wall construction is used.

Other environmental assessments were developed in the field of hemp–lime concrete wall by Nordby and Shea [90]. They carried out a study aimed at exploring how responsible use of building materials can yield environmental benefits that can be quantified in a life-cycle perspective. This was done by investigating and comparing carbon impacts related to the following three design concepts for an exterior wall: (A) concrete/rock wool; (B) wood studs/wood fibre; and, (C) wood studs/hemp–lime concrete. The life-cycle of the wall was set to 60 years whilst, similarly to Ip and Miller [20], only GHG-emissions were considered for the assessment. The analysis of the exterior walls regarded four areas of environmental impacts: the embodied carbon of the materials, reflecting manufacturing loads and transport to the building site; the sequestered carbon in plant-based materials and re-carbonation in lime and concrete; thermal buffering and the potential reduced energy impact caused by using materials with heat capacity in the interior; and, finally, the moisture buffering and the potential reduced energy impact due to the use of hygroscopic materials. According to the authors, the obtained results show that concept A has the highest embodied carbon and that its potential for carbon storage and re-carbonation is 12% to 20% of the manufacturing loads in a 60-year lifespan and, therefore, very low compared to the other analysed concept-walls (B and C). In fact, for these two, the carbon storage and re-carbonation potentials are 122% to 240% and 208% to 400% of the manufacturing loads, respectively: this is in agreement with Ip and Muller [20]. Finally, with regard to the buffering effects, wall A has the highest potential for thermal buffering since concrete is a good medium from this point of view. On the contrary, walls B and C have the highest potential for moisture buffering and thus enable greater saving of the operational energy for heating and cooling compared to concrete-base wall (concept A). Based upon these findings, hemp-concrete walls present high energy efficiency and environmental quality and, for this reason, should be preferred to conventional concretes walls.

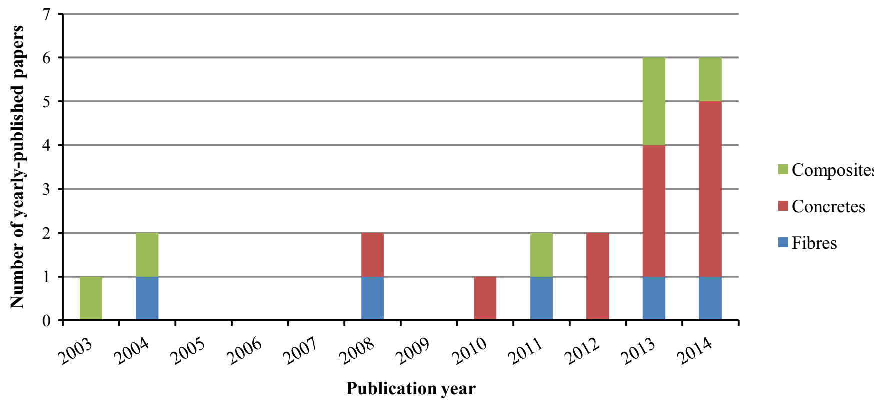

Fig. 7. Number of publications dealing with energy and environmental assessments in the field of hemp based materials[4].

5. Results and discussions

The review performed highlighted twenty-two papers, published between 2003 and 2014 dealing with assessment of the energy and environmental performances of hemp-based building materials, such as mats, lime-based concretes and bio-composites (see Fig. 7).

Based upon the findings of the reviewed studies, it was observed that, though some of them were published in 2003, 2004, and 2008, mainstream research began in 2010 with the greatest number of publications falling in between 2010 and 2014. In particular, twelve studies were published in the period 2013–2014, thus representing more than half of the total number of publications reviewed between 2003 and 2014. This aspect is mainly attributable to the growing interest and attention towards the field of production and application of hemp-based materials by the involved stakeholders, such as designers, researchers, builders and company owners. These stakeholders are increasingly becoming aware of the energy and environmental benefits resulting from using these materials in buildings. Therefore, they perform assessments of the related structural, mechanical, energy, and environmental aspects in order to enable further improvement and innovation of these materials as well as of the construction technologies involved.

A greater number of studies dealing with analysis of physical, mechanical, hygric, and thermal properties was found compared to the ones regarding environmental assessments: this can be considered as due to the priority that the structure and energy issues have over the environmental ones. These biomaterials have to be designed to be competitive based upon their architectural, structural, and hygrothermal performances and, therefore, to represent a valid alternative to conventional materials. From Fig. 7, it can be noticed that hemp-concrete is the most investigated sector with eleven published papers, followed by composites and fibres. It can be concluded that the increasing production and utilisation of hemp-concrete is principally because it can be used as such without any additional material to fill load-bearing structures whilst providing thermo-acoustic insulation. The hemp-concrete's thermal conductivity is strictly connected mainly to hemp and water content, to binder type and content, to relative humidity and moisture percentage, to material density and hardness as well as to production technologies. The environmental assessments conducted pointed out, both directly and indirectly, that hemp-concrete appears to be an environmentally friendly material and that its environmental quality could be further improved by reducing the impact coming from production of the binders used. The researchers have started working on testing the feasibility of producing low environmental-impact binders, whilst preserving their overall quality. This could enable the preservation of the structural, mechanical, hygrothermal properties of the concrete for use in building applications.

Focussing upon the environmental issue of all the analysed hemp-based materials (mats, concretes and composites), numerous studies were found and many others are expected to be conducted in future due to the growing interest towards the field and also due to the necessity of assessing (from an environmental point-of-view) the already structurally and thermally tested materials. These assessments were believed relevant because they gather more knowledge on the environmental issues associated with these materials. Furthermore, they contribute to enriching the international discourse on the energy and environmental soundness associated with the use of these materials in buildings, by providing reliable information on both data inventoried and results obtained. The studies were based upon life-cycle assessments both of the global environmental impacts and of the impact on climate change, measured as GWP-100, coming from crop production and from processing into building materials. These studies provided the choice of the FU and the definition of the system boundaries in order to be consistent as established by the related international standards. In particular, the FU was found to be not always quite clearly identified but, most of all, to be mainly dependent upon both the type of hemp-product and the objectives of the study. This aspect emphasises on the absence of agreement on the FU to be considered in order to facilitate comparison between similar products and, also, on the need of its accurate choice in order to avoid affecting negatively the findings of the study. The system boundaries were designed so as to include hemp cultivation, thus accounting for all the main input flows involved such as, for instance, seed production, fertiliser production and administration, fossil fuel use for agricultural activities and for transportation. The environmental assessments reviewed are those: of Zampori et al. [75] and van der Werf [77] in the field of hemp fibre; of Ip and Miller [20], Nordby and Shea [90], and Pretot et al. [87] for what concerns hemp concretes; and, finally, of Pervaiz and Sain [80], Joshi et al. [17], Bourmaud et al. [81] and, La Rosa et al. [22,83] dealing with bio-composites. The latter is the most environmentally investigated sector amongst those considered, followed by concretes and fibres.

In the field of bio-composites, the studies reviewed highlighted that hemp fibres should be preferred to glass ones. According to some authors, this is mainly because: (1) their production results in lower environmental impacts compared to glass fibre production; (2) hemp-based composites have higher fibre content for equivalent performance, which reduces the amount of more polluting base polymers; and (3) lower weight of hemp-fibre based composites improves fuel efficiency and reduces emissions during the use phase

[4] Based upon papers detected during the literature review performed (from 2003 to 2014).

of the component. The use of hemp fibres for bio-composite applications, as for concrete and insulation mat, act as 'sink' for atmospheric CO_2 due to the amount of CO_2 that is up-taken by photosynthesis during plant growth. This contribution is indeed so high that it overcomes the emissions of fossil-CO_2 due to the cultivation and processing phases so much that a negative total-value of tCO_{2eq} per ha of cultivated land can be obtained. For instance, Zampori et al. [75] showed that CO_2 uptake and emission contributions are equal to -27.6 and 1.57 tCO_{2eq}/ha, respectively, thus resulting in a total of -26.03 tCO_{2eq}/ha sequestered. Carbon sequestration in biomass has the greatest effect and, also, would lead to a change of perception if it was included within schemes providing carbon accounting. When buildings are located in warm climate areas, where high temperatures are recorded during summer and, so, cooling is particularly needed, thermal buffering effects, together with other solutions like those proposed by Maalouf et al. [31], may also become significant and, for this reason, alternative materials, like conventional concrete, could be used. In this regard, it should be observed that buildings are unique to their environment and, therefore, there exist limitations to the usefulness of standardising and up-scaling similar solutions. Moreover, all the energy and environmental assessments reviewed and discussed above, as any other developed, can be considered as top-down exercises. Therefore, it can be concluded that architectural design, being an interdisciplinary practice, rather represents a bottom-up approach, which is decisive for the overall sustainability of buildings in their life-cycles [90].

6. Conclusions

The increasing consideration of natural resources and energy conservation has recently renewed the interest on biomaterials and, in particular, on new ecologically friendly materials based upon fast-renewable natural sources. In particular, for sustainable building construction it is fundamental to use materials which are designed to have low environmental impact and low GHG-emission. Recent advances in the development of natural fibres, such as those from hemp, flax and jute, as well as in the science of composite materials, represent a significant opportunity for production of improved-materials from renewable resources and energy. Therefore, the authors believe that assessments of both energy and environmental performances are needed as tools for supporting both the design and the production of those materials with the aim of identifying solutions for enhanced contribution to global sustainability. This study presented a review of the papers that have been developed in recent years focussing upon assessment of the environmental and energy issues related to the use of hemp-based materials for series of building applications. Based upon the findings of the review-study carried out, it can be concluded that a significant increase in the number of energy and environmental studies on building materials for envelope thermal insulation and for other building applications has been recorded in recent years. Those studies aimed at testing and improving hygrothermal properties and eco-friendliness of these materials so as to enable reduction of both embodied and operational energy, whilst preserving both indoor air quality and comfort. This would allow for limited exploitation of energy resources and for limited impacts to human health and to the environment, thereby contributing to make buildings healthier and more environmentally sustainable during their life-cycles. The reviewed literature demonstrated that these materials have strengths and weaknesses and that their use is strictly dependent upon the given structural situation and also upon specific requirements of thermal, moisture, fire and sound protection. The main strength in the use of hemp-based materials comes from the production phase because of the "green" origin of these materials, mainly associated with the carbon sequestration during plant growth. However, industrial hemp products, as with most of the renewable raw materials available nowadays, generally score better than conventional materials (such as those made of glass fibres) with regard to the use of fossil fuel and to the emission of GHGs. On the contrary, they score worse when it comes to land use, eco-toxicity, and eutrophication because of the surface invested for cultivation and of the use of chemicals for fertilisation and pest management. This limit could be overcome by a greater rotation of the crops and also by the application of conservation agriculture systems based upon no-tillage and organic farming.

The review performed allowed the authors to understand that life-cycle energy and environmental analyses of buildings are needed to be performed for better identification of those materials and technologies usable for construction of buildings so that the latter are characterised by low rates of energy consumption and environmental impact. In particular, all the detected LCA-studies showed that replacing conventional thermal insulating materials with sustainable materials like industrial hemp products, lead to reduced environmental impacts of all the different phases of the building's life-cycle. Despite of the energy and environmental soundness of hemp-based materials, there exist principally-economic weaknesses which, in the authors' opinion, can result in negative prospects for the future of industrial hemp. In particular, as highlighted by Carus et al. [91], hemp fibres have a two to four times higher cost price compared to conventional materials such as glass and mineral wool that are currently dominating the market. Also, hemp suffers from unfair competition by subsidies for biofuel and bioenergy crops: in this regard, adjustment of the current EU-policy could restore healthy competition between these crops, thus giving industrial hemp the possibility to overcome barriers faced during its infancy phase.

All that considered, the authors believe that hemp can compete with conventional materials only in terms of technical quality, primary energy, and eco-compatibility and that, for now, the "hemp business" depends upon specific demand by sustainability oriented customers. Nonetheless, they expect that the use of hemp for buildings applications will grow considerably in the near future since such a material holds a great potential in the development of bio-based economies. According to the authors, this aspect will lead to increased development of other researches designed for assessing and improving both energy and environmental aspects of hemp-based materials. In this way, it will be possible to further contribute to their global quality improvement as well as to enhancement of both knowledge in the field and availability of useful data on construction materials and technologies for more sustainable and energy-saving buildings.

As a consequence, the authors believe that series of frameworks will be created in the near future for the design of appropriate public policy oriented to development and promotion of the aforementioned materials and technologies. Finally, this aspect could include also adjustment of the current EU-policy in order to provide subsidies to producers and users of hemp-based materials, so as to enable enhancement and differentiation of their applications in the industry.

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