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REVIEW PAPER

A review on recent research on bio-based building materials and their applications

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Abstract
Bio-based materials represent a promising alternative in building envelope applications, with the aim of improving in-use energy efficiency. They have the advantage of being renewable, low embodied energy and CO_2 neutral or negative. In addition, they are excellent thermal regulators. This paper presents an overview of the state-of-the-art of bio-based materials used in building construction and their applications. The materials outlined include hemp, wood, date palm wood, cork, alfa and straw. Through this literature study we want to get a broad overview of the current state of theoretical and experimental studies of their hygrothermal characteristics and their thermal and energy performances. The aim is not to be exhaustive but to summarise the most important research results on these materials. This is the first part of a research work that deals with the contribution to the development of a new bio-based construction material to be used in building.

Keywords Energy efficiency · Bio-based materials · Thermal conductivity · Moisture buffering value

Introduction

The building sector, one of the most energy-intensive sectors, accounts for about one third of global primary energy demand which represents a major source of energy-related greenhouse gas (GHG) emissions [1]. The United Nations Global Status Report 2018 [2] estimates that building construction and operation accounted for 36% of global final energy consumption and nearly 39% of energy-related carbon dioxide (CO2) emissions in 2017 (Fig. 1). Similar values have been observed by European Commission studies [3].

Final energy consumption in buildings has increased from 118 EJ in 2010 to about 128 EJ in 2019 [4]. As a result, direct emissions from buildings reached just over 3 Gt CO in 2019, a 5% increase since 2010. If current trends continue, buildings will be the world's largest energy users by 2025, consuming more energy than the transportation and manufacturing sectors combined [5]. The building industry uses a significant number of raw materials and consumes a lot of resources. 60% of the raw materials derived from the lithosphere are used in civil engineering and building construction [6]. The building industry accounts for 40% of this amount, or 24% of the total extraction. The most primary energy is consumed during the processing process [7].

The manufacturing of construction materials accounts for more than 80% of the energy consumption of building construction [8]. The direct CO_2 intensity of cement production increased by 0.5% per year from 2014 to 2018 [4]. It is commonly accepted that the manufacture of one tonne of cement emits nearly one tonne of CO_2, that more than 60% of CO_2 emissions are produced during the "decarbonation" phase and that cement production accounts for about 5% of total CO_2 emissions. Algeria, a country in the Mediterranean region, is facing the triple challenge of increasing construction sites in response to a persistent housing crisis and a growing population. The building sector accounts for roughly 43% of the country's overall energy consumption [9]. In addition, the building materials sector is the most energy-intensive branch of industry. According to the

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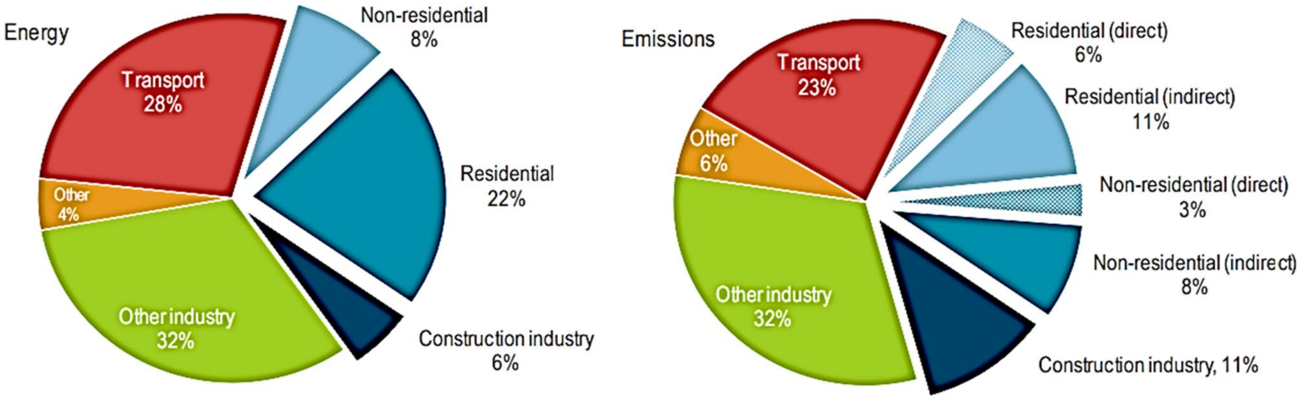
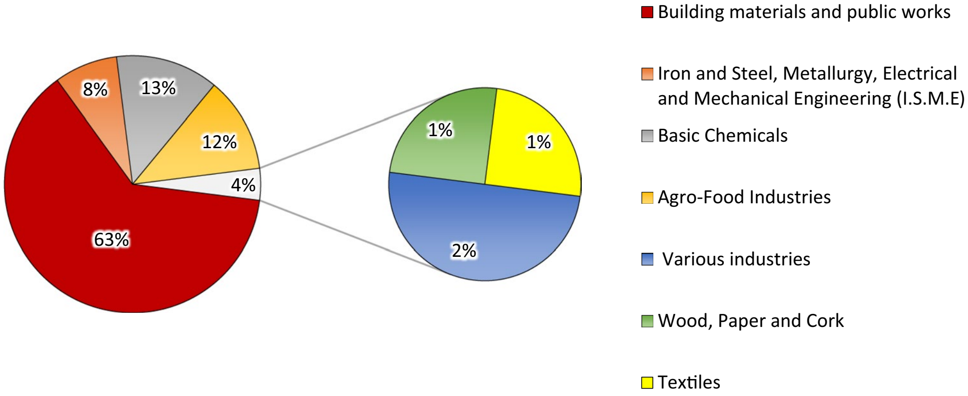


Fig. 1 Buildings and construction's global share of final energy and pollution in 2017 [2]

Fig. 2 Distribution of industry sector consumption by branch [9]



APRUE report [9], this branch consumes around 63% of the energy of this sector (Fig. 2), a growing share of the industrial energy balance, rising from 19% in 2005 to 22% in 2017. Power industries are the leading source of GHG emissions, accounting for 32.30% of total emissions. Residential and transportation come in second and third, with 16.24% and 14.60%, respectively [10].

Building energy efficiency is currently a top priority for foreign energy policymakers. The integration of energy efficient policies, practices and behaviours for a change towards a more environmentally friendly culture is necessary. This requires a carbon-centric approach, which is the main driver of the GHG emissions footprint. Several environmental policies, including the Energy Performance of Buildings Directive in Europe (EPBD, [11]) and the Energy Efficiency Directive, have been defined in Europe (EED, [12]). In comparison to 2005 results, the European Commission estimates that these actions will help reduce energy demand for heating and cooling by 8% in 2020, 12% in 2030, and 17% in 2050 [13].

Following the example of the entire world, Algeria should have a showcase in the field of green building technology, environmental preservation and sustainable development. It is becoming imperative to migrate towards new construction methods that take into account the imperatives of energy sobriety. Moreover, several measures have been initiated by the government to improve the quality of housing construction and to encourage the use of local building materials. A new version of the Algerian thermal regulation for buildings was published in 2016 by the Ministry of Housing, Urbanism and Town Planning [14]. The application of these thermal regulations must lead to the compulsory thermal insulation of new buildings, with the objective of reducing heating and air conditioning energy consumption. It should be noted that, like a large number of African countries, Algeria does not currently impose the application of thermal specifications and regulations to buildings.

Increased environmental awareness is driving the use of green and high thermal performance building materials. The use of bio-based materials is becoming a key to improving the energy efficiency of buildings, providing both environmental and economic benefits [15, 16]. The use of plant-based biomass materials in construction can help to reduce fossil energy demand, protect the environment from carbon dioxide and reduce the production of non-degradable waste. The positive environmental impact of these materials with

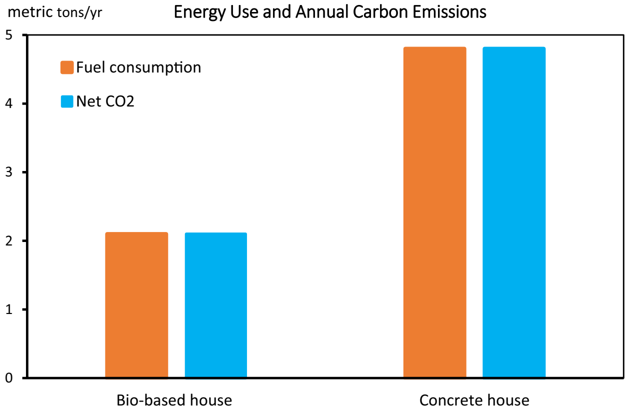


Fig. 3 Annual carbon emissions for bio-based and concrete houses [19] (Readapted by the authors)

regard to the criterion of combating global warming is due to the consideration of biogenic carbon stored by plants [17], as shown in Fig. 3. They are excellent thermal regulators. In contrast to conventional thermal insulation, biobased insulation is made from renewable materials and carries a very low embodied energy and contributes significantly to minimise thermal loads in buildings and thus to moderate energy consumption. Their effectiveness depends mainly on the value of thermal conductivity which depends on the density, porosity and moisture content of the material [18].

Many recent scientific studies have focused on the search for innovative, bio-based insulation materials and their incorporation into building envelopes. According to a recent case study on a hypothetical building model in Finland, cellulose fibre insulation has the lowest life cycle energy balance of all building materials, including expanded polystyrene and glass wool insulation [20]. A growing body of published studies in which life cycle assessment is applied to evaluate the impact of different building materials suggests that building with eco-materials can result in lower energy consumption and CO_2 emissions than other materials such as concrete, brick or steel [21–23]. In this study, we recapitulated the research that has focused on plant resources as building and insulating materials and that are considered the most available in the Mediterranean and North African region and discussed and presented the availability of plant resources and the hygrothermal and energetic performance of eco-materials at envelope scale.

Bio-based materials

A building material is said to be biobased when it incorporates plant or animal biomass. Biomass is a material of biological origin, with the exception of materials of geological or fossil formation [24]. Their raw material is therefore largely derived from renewable resources and mainly uses co-products from agriculture or the wood industry. Unlike other types of insulation materials, most bio-based materials exhibit hygroscopic behaviour, combining high water vapour permeability and moisture regulation [25–29].

Table 1 Comparative table on the fields of application of bio-based materials

Materials	Packaging	Areas of application			
		Wall	Ground	Floor	Plaster
Wood	Wood wool	×		×	
	Wood in bulk	×		×	
	Solid wood	×	×	×	
	Wood concrete	×	×	×	×
Straw	Straw bales	×		×	
	Straw panels	×		×	
	Straw earth plaster	×			×
Date palm wood	Date palm concrete	×	×	×	×
Alfa	Alfa concrete	×	×	×	×
Cork	Panels/rolls	×	×	×	
	Bulk	×		×	
Hemp	Hemp	×		×	
	Hemp wool	×			
	Precast concrete	×	×	×	
	Shotcrete	×		×	×

Application of bio-based materials in the building sector

Bio-based materials are now used in a variety of building applications, including load-bearing, filling, insulating, and plastering materials [30]. These materials vary in structure depending on the formulation used (Table 1) [30, 31]. Plant fibres can be combined with binders and then used in construction to provide thermal, hydric or structural functions. The behaviour of concrete based on plant fibre is mainly governed by the amount of the fibre constituting the material. Several studies have shown that increasing the amount of these plant particles increases porosity, moisture buffering capacity, and maximum absorbed water content on the one side, while decreasing density, thermal conductivity, and compressive strength on the other.

Thermal and hydric characteristics of bio-based materials

The behaviour of an insulating material is strongly related to its thermal and hydric characteristics. In the following paragraphs, the key parameters that express these thermal and hydric performances will be addressed. The aim of eco-materials is to reduce heat flow transmission. Eco-materials aim at reducing the transmission of heat flow. The thermal insulation performance of materials is conditioned by the thermal conductivity λ and the thermal transmittance for the stationary state and the thermal diffusivity D for the unstable state. Thermal conductivity is the heat flow through a unit area of a homogeneous material of 1 m thickness induced by a temperature difference of 1 K on its faces. It is expressed in W m^{-1} K^{-1}. and is measured according to EN 12664 (low thermal resistance) [32], EN 12667 (high thermal resistance) [33], EN 12939 (thick products of high and medium thermal resistance) [34], ASTM C518 (heat flow meter apparatus) [35], or also ASTM C177 (guarded hot plate apparatus) [36].

The thermal transmittance, U, is the amount of heat that flows through a unit area of a complex component or heterogeneous material due to a temperature gradient of 1 K; it is measured in W/m^2 K. For a multi-layer wall, the thermal properties are expressed by the thermal transmittance with the ISO 6946 calculation method [37]. The procedures described in ISO 13786 can be used to perform more detailed thermal characterisation of building components for unstable conditions [38]. The ratio of thermal conductivity to the product of density and specific heat power is used to measure thermal diffusivity D. It is expressed in m^2/s and is a derived quantity composed of the intrinsic properties of the material. It is measured in accordance with ISO 22007-1 (general principles) [39], ISO 22007-2 (transient plane heat source method) [40], ISO 22007-3 [41] (temperature wave analysis method) or ISO 22007-4 [42].

The specific heat defines the capacity of a material to store energy. It is the heat required by 1 kg of material to change its temperature by 1 K, expressed in J/(kg K) and measured according to ISO 11357 [43] or ASTM E1269 [44]. Vapour permeability is the ratio of the amount of water vapour passing through a material per unit thickness, per unit time and per unit vapour pressure difference across the material. It provides data on the moisture migration in these materials, which is usually attributed to a vapour diffusion process. Vapour permeability is calculated using the cup method according to EN ISO 12572 [45]. It is expressed in Kg/(m s Pa).

The water vapour resistance factor μ is a dimensionless parameter used to assess a material's potential to be non-permeable to water vapour. The lower the value, the higher the vapour permeability of the material. The μ-value of 1 is assigned to air. The μ-value of insulating materials can be determined by means of EN 12086 [46] and EN 12088 [47], which define the procedures for quantifying the amount of water absorbed by long-term diffusion. The moisture buffer value (MBV) is a metric that is used to compare and characterize the moisture buffering capacities of various building materials. MBV is defined as the change in mass per square metre per change in relative humidity g/(m^2 % RH). The moisture buffering capacity of a material represents its ability to absorb or release moisture, and it indicates how well it can moderate changes in indoor humidity in a building. There is currently no standard for this test, but the NORDTEST project [48] proposes a standardized test protocol.

Wood

Historically, wood has been and remains an environmentally friendly and widely used structural material [49]. In 2016, sawn wood production in Europe and North America totalled 122 million m^3 and 128 million m^3, respectively [50]. It allows the creation of construction products such as load-bearing structures, cladding, joinery, wood panels, wood wool or wood fibre in bulk for implementation by blowing or insufflation and possibly with the addition of binder depending on the application. Despite the country's forest wealth, wood is seldom used in Algeria. A total of 3.7 million hectares are covered in forests. The Aleppo pine is the dominant species. The total area used for timber processing and pulping (excluding cork oak) is projected to be 1,038,000 ha, with an annual availability of about 750,000 m^3/year [51].

The properties associated with wood's thermal behaviour, as well as moisture transfer, are evaluated on a macroscopic scale. The thermal conductivity of wood is affected by a variety of factors, including the form of wood used, measuring direction (perpendicular or parallel to the fibres), density, and moisture content [26]. Wood and wood products have much lower thermal conductivity values than other structural building materials [52]. It is roughly ten times lower than

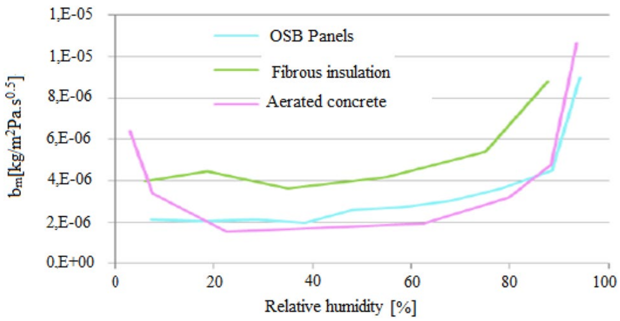


Fig. 4 Moisture storage capacity b_m as a function of relative humidity [26]

concrete and 250 times lower than steel. Indeed, the conductivity of most woods ranges from 0.038 (for wood fibre) [53] to 0.192 W m^{-1} K^{-1} (for solid wood) [54].

As far as hydric performance is concerned, these materials show very interesting hydric properties. Figure 4 shows the moisture storage capacity b_m in relation to relative humidity. It shows the materials' ability to exchange moisture with the ambient air, with wood fibre insulation having the highest level of moisture absorption or release followed by aerated concrete and then OSB. Moisture buffer values for different wood materials range from 0.87 to 3.5 g/(m^2%RH) [26, 55] and the Water vapour diffusion resistance factor from 1 to 812.8 [53, 56].

Stazi et al. [57] investigated the actual performance of a super-insulated wood envelope in a Mediterranean climate residential house. The monitoring of the comfort conditions showed the presence of considerable overheating of the indoor environments. The overheating is also due to the high air tightness of the envelope. According to the study [57], numerical research has shown that such a problem can be reduced by adopting a combination of the following appropriate cooling strategies: the incorporation of an internal solid layer, as well as brick counter walls or a double layer of thin dry clay panels, the use of hybrid ventilation and the adoption of Controlled Mechanical Ventilation (CMV) + free cooling. The combination of these strategies can reduce discomfort levels by up to 50% in temperate climates, 31% in semi-arid climates and 6% in desert climates.

A dynamic simulation, using TRNSYS software, was carried out on a building in Longwy (Lorraine, North-East France) by Mnasri et al. [55] to evaluate the cooling and heating needs. Various insulation scenarios were investigated. They showed that insulation significantly reduces the total energy demand, but it does not result in heat removal during the summer season, so they concluded that a natural ventilation system is recommended to increase the building's energy efficiency. According to Li et al. [58], wood-cement composite materials can contribute to improve indoor indoor thermal comfort and are useful in the building of low-energy buildings. A strong moisture buffer capacity was discovered, confirming the new wood-cement composite's ability to control indoor humidity.

Several studies in the last decade have looked at the distribution of impacts through the various phases of the wood building cycle [57, 59, 60]. Wooden buildings, in addition to low energy requirements, have advantages in other stages of the life cycle, such as: low weight of building materials, lowest amount of waste during the life cycle, lowest transport impact and lowest water and energy consumption on site. Figure 5 shows Life cycle phases of a passive house for 75 years and results from the construction phase

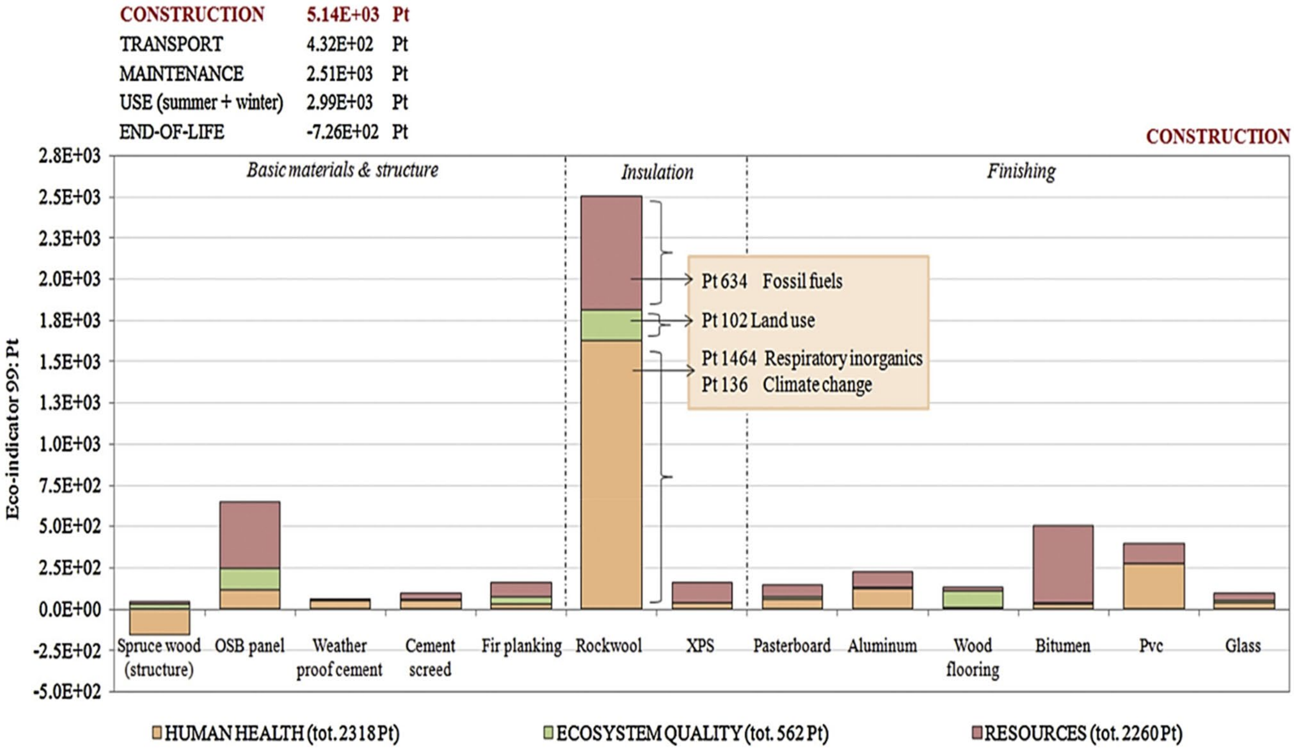


Fig. 5 Life cycle phases of a passive house for 75 years and results from the construction phase to year 0 according to the Eco-indicator 99 method [57]

to year 0 according to the Eco-indicator 99 method [57]. The approach calculates the "environmental damage" in terms of numbers or scores in three categories:

- Human health: the impacts are included mainly as a result of the following: climate change, ozone layer depletion, carcinogenic effects, respiratory effects, and ionization.
- Ecosystem quality: this category accounts for the impact on species diversity, acidification, eco-toxicity, eutrophication, and land use.
- Resources: this category basically represents the depletion of raw materials and energy resources. It is measured in terms of the surplus energy required in the future to extract lower-quality energy and minerals.

The figure shows that the wooden house energy requirements are lower than those of masonry and mineral insulated buildings. The highest impact, according to the graph, can be attributed to insulation materials, especially rock wool insulation with the highest damage on the human health. In fact, the formaldehyde based binders used during the production process (to bond the rock fibres) cause respiratory effects mainly due to winter smog. Moreover, the greatest impact on "Resources" category is caused by "fossil fuels" sub-category due to the high burdens associated with the production activities: the volcanic rock is melted, transformed into fibres and sprayed with resin and oil, then sent to polymerization furnaces.

Similarly, Schneiders et al. [61] found that compared to all other building materials, the energy required to construct, maintain, and recycle wooden houses is the least. Every cubic metre of wood used as a replacement for other materials decreases CO_2 emissions by an average of 1.1 t into the atmosphere. H. Cho et al. [62] compared the energy consumption of internal and external insulation systems when analysing the hygrothermal properties of cross-laminated timber (CLT) walls. The energy efficiency of a CLT wall with external insulation is higher than that of a CLT wall with internal insulation. To improve the building's energy efficiency by reducing thermal bridges, it is critical to reduce heat loss in the architecture. A Canadian study found that using I-Joist wall studs and staggered wall systems to increase the gap between wood framing studs improves thermal resistance efficiency compared to a traditional wall system [5].

Date palm wood

Fig. 6 Photo of a date palm [63]

The date palm (Fig. 6) is grown in semi-arid areas for date production. There are approximately 105 million palm trees in the world, occupying an area of 800,000 ha. In Algeria alone, a date palm with an average of 13 leaves and petioles and 7 bunches per year produces around 210,000 tonnes of date palm petioles, 73,000 tonnes of leaves, and 52,000 tonnes of bunches. Petioles, 410,000 leaves, and 300,000 bunches are produced annually in excess of 12 million tonnes worldwide. As a consequence, the use of date palm waste fibers is a successful project from both an economic and environmental perspective [63]. The use of date palm fiber as a concrete reinforcement and a natural material for building thermal insulation appears to have been extensively researched [28, 64–67].

In Ghardaia, Ksour of Djanet and other regions of southern Algeria, old palm trees are traditionally used in the construction of mud houses (Fig. 7). This use is manifested by the presence of trunks at the level of the structure (post–beam), leaves and the base of the petioles at the level of the floor.

Date palm wood, according to the authors in [68], is a good candidate for the production of less costly materials for use in the field of thermal insulation. The results of the experimental analysis of the thermo-physical properties of palm wood extracted from various palm tree varieties revealed thermal conductivity values of less than 0.2 $W\ m^{-1}\ K^{-1}$ [63, 69, 70]. Tlijani's thesis work [69] focused on palm wood samples collected from the trunks of three types of date palms: Deglat, Ftimi, and Rtoub, as well as Deglat palm petiole. Table 2 summarizes the thermal conductivity results.

The thermophysical properties of date palm wood are also affected by fibre orientation. A novel bio-composite material made from gypsum and date palm fibres was also investigated. The thermal conductivity was between 0.091 and 0.201 $W\ m^{-1}\ K^{-1}$ and the density was between 680 and 968 kg/m^3 [70–72]. Several works have proven that the concentration of date palm wood in the matrix and the choice of binder directly influence thermophysical properties of Date Palm Concrete (DPC). Cement and gypsum were used to test

Fig. 7 Use of palm (trunk and leaves) in construction [68]

Table 2 Thermal properties of wood fibres of different palm varieties[69]

Type of palm	λ (W m^{-1} K^{-1})
Deglat	0.168
Ftimi	0.144
Rtoub	0.102
Palm stalk	0.058

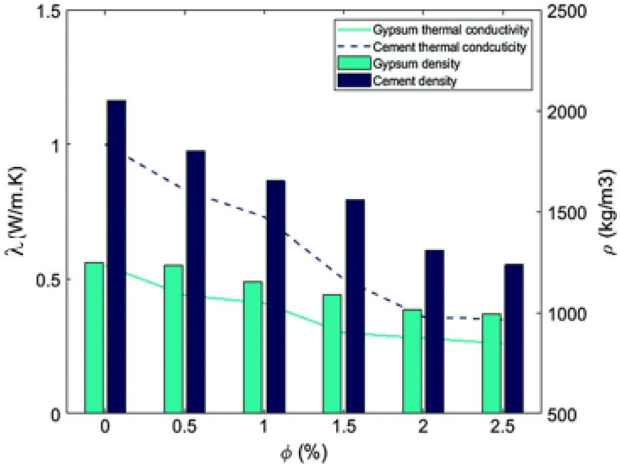


Fig. 8 The composite's thermal conductivity and density as a function of the fibre ratio [73]

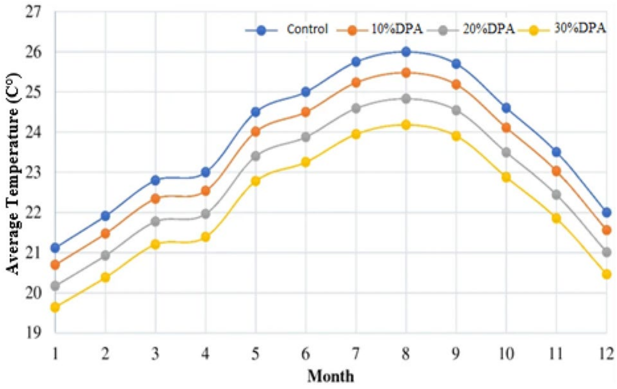


Fig. 9 Average monthly variation of indoor temperature for various wall options [77]

the binders. Figure 8 shows that as the fibre ratio increases, all mortars' dry densities and conductivities decrease. Furthermore, the density of gypsum mortar is lower than that of cement mortar.

The vapour permeability of DPC varies from 2.22×10^{-11} kg/(m.s.Pa) to 3.59×10^{-11} kg/(m.s.Pa). It is affected by changes in the fibre/binder ratio and is dependent on moisture content [28, 74]. For the moisture buffer, average values between 1.79 and 4.05 g/(m^2.%RH) are found according to the authors [28, 72, 75, 76]. The thermal and energy efficiency of masonry blocks made with date palm ash (DPA) and ordinary Portland cement was evaluated by Ashraf et al. [77]. Indeed, a typical office building in Dhahran (KSA) was subjected to energy simulations. They discovered that the thermal resistance of the block loaded with 10%, 20%, and 30% DPA increased by 9.6%, 8.1%, and 47.4%, respectively, as compared to the control block (0% DPA). The use of DPA-based blocks resulted in an 11.3% decrease in the building's annual energy consumption as compared to traditional masonry blocks. DPA content in masonry blocks, according to these writers, is a promising choice for reducing thermal stress within the house, as shown in Fig. 9.

Mokhtari et al. [78] investigated the impact of using a new natural durable insulation material available semi-hydrated gypsum/date palm fibre (HG-DPF) for exterior walls on the interior thermal behaviour under the arid climatic conditions of the city of Bechar using TRNSYS simulation software under stable periodic conditions (southern Algeria). Several configurations of exterior walls are proposed. These configurations are based on the alteration of two aspects: wall building materials using stabilised earth blocks (SEB) and clay bricks, and insulation materials using polystyrene and a new referenced biocomposite insulation material (HG-DPF). In comparison to the other wall configurations studied, the results show that the wall configuration consisting of SEB and HG-DPF interior insulation materials provides the best thermal efficiency.

Chennouf et al. [66] investigated the hygrothermal behaviour of a wall structure made of a new biosourced date palm concrete (DPC) material. A simple bioclimatic configuration was designed to apply stable or dynamic boundary conditions on the exterior side of the wall, while the interior environment was set at 23 ℃ and 50% RH at the initial time and left uncontrolled during the experiments. The results showed that this material is a good candidate to limit overheating during summer and to dampen temperature variations and has interesting hygienic performance due to the date palm fibres, which can help to mitigate relative humidity variations.

As compared to sandcrete blocks, Opoku et al. [67], estimated a potential annual electricity savings of 453.40 kWh for cooling an office space in Sub-Saharan Africa using the treated sand-palm fibre composite as a building envelope. The presence of palm fibres to the cement mortar improves the system's porosity. This increases the material's water vapour permeability and would therefore probably contribute to the breathability of the building [79]. A numerical comparison was made between DPC and a conventional building material in terms of thermal insulation and moisture buffering capacity. The findings revealed that the new bio-based wall would help minimize temperature fluctuations and increase building hydrothermal comfort [80, 81].

Fig. 10 Stems of Alfa plant [83]

Fig. 11 Alfa fibre in Algeria [85]

Alfa fibres

The alfa "esparto grass" or Stippa Tenacissima (Fig. 10) is widely cultivated in the dry and arid region of North Africa (warm Mediterranean region). It can also be found in the central regions of south-eastern Spain and the Balearic Islands of Iceland [82].

In Algeria, the world's largest producer (Table 3), the Alfa plant grows independently forming patches (Fig. 11). Alfa is a great buffer against desertification and desert encroachment in Mediterranean countries, and its cultivation is environmentally friendly because it does not require insecticides or pesticides and needs little water for growth [84]. It is most commonly used to make high-quality paper, but is also used in the manufacture of ropes, espadrilles, coarse fabrics, mats and baskets. In terms of construction, in arid regions, houses are built with traditional walls made of earth and Alfa fibre.

For some years now, Algerian researchers have been very interested in the development of new composites reinforced with Alfa fibres as an essential component of an insulating material for the building and civil engineering sector [85–89]. This research identifies some key properties of this plant. Alfa fibres consist mainly of 39.53% cellulose, 27.63% hemicellulose, 19.53% lignin and other extractives [83]. Alfa has a low bulk density (99 kg/m^3) and a total porosity of about 92%, where the pore diameter is between 3 and 10 µm. A low absorption coefficient (56%) compared to other vegetable particles such as hemp (300%), which promises to improve the setting time and mechanical properties of the manufactured concrete. Low thermal conductivity values have been reported for these fibres, of the order of 0.058 W m^{-1} K^{-1} for a density of 120 kg/m^3 Alfa [89].

Table 3 Territorial distribution of Alfa plant in some regions [82]

Country	Algeria	Morocco	Tunisia	Libya	Spain	Portugal
Area (ha)	4.000.000	3.186.000	600.000	350.000	300.000	Few

Thus, Alfa aggregates can be considered as an alternative material for the production of ecological concretes based on a mineral matrix. Tests conclude that alfa fibres are very flexible and have a very high hydrophilic capacity [88] and that composites based on these fibres have a good consistency. Mechanical tests on these composites show that the strength decreases with increasing fibre percentage [85, 87, 88, 90]. Their thermal conductivity varies from 0.372 to 0.8 W m^{-1} K^{-1}, and the density from 1583.25 to 2075.60 kg/m^3 [90–93]. These studies also show that increasing the percentage of Alfa fibre is beneficial for improving energy performance and reducing density (Fig. 12). Despite its availability in Algeria, the use of Alfa in construction is very limited. Little work has been done on its thermal, hydric and energetic performance as insulation or as Alfa fibre concrete on a material scale.

Straw

Straw (Fig. 13) is a by-product of cereal crops such as wheat, maize, rice, barley, oats, rye and sorghum, after the cereals have been harvested. Straw is mostly made up of cellulose and lignin, which are the same main components of wood [94]. It is widely available and inexpensive in many countries, especially in the Mediterranean region. Straw was one of the first materials to be used in green buildings. Usually, straw for building comes from wheat farming [13]. With the invention of the steam press in the late 1800s, the first straw bale buildings were built in Nebraska, USA [95]. For centuries in Asia, Africa, and Europe, walls made of bound straw bales covered with clay were constructed. It is making a comeback in the form of straw bales, which are used as insulation, plaster support, straw concrete, and as fibres in mud bricks. In Algeria's hot climates of Biskra, Oued Souf, Ghardaia, Timimoune, and Adrar, it is primarily used in envelopes as fibres blended with raw earth with a lime and plaster coating [51]. In contrast, in Kabylia region, the walls of traditional houses are plastered with clay, cow dung, and straw. The same clay paste, but without straw, is used as mortar to build the walls.

Fig. 13 Straw bale [96]

The use of straw bales as thermal insulation in buildings has been studied by many authors [25, 51, 97–99]. They mainly focus on the straw's thermal and hygrothermal properties. The findings showed that using straw in construction improves energy, environmental, and economic efficiency.

The hygrothermal properties of straw bales have been measured and reviewed in several technical papers [25, 97–103]. According to research, the thermal conductivity does not differ significantly depending on the type of straw [104]. Samples with densities between 63 and 350 kg/m^3 have been analysed [98, 99]. The best performing was characterised by a thermal conductivity of 0.038 W m^{-1} K^{-1} [98]. Marques et al. [101], Reif et al. [103] and Cascone et al. [99] indicate that the thermal conductivity of straw is relatively insensitive to bale density. The thermal conductivity of straw bales has been shown to differ with the direction of the straw's orientation within the bale, with straws with fibres oriented perpendicularly or randomly to the heat flow having lower thermal conductivity than those arranged in parallel [102, 105], as shown in Fig. 14.

For different temperatures and densities, Vjelien [105] studied four variations of the same kind of straw: two variations concerned the direction of the fibres in relation to the heat flow: perpendicular and parallel, and the other two

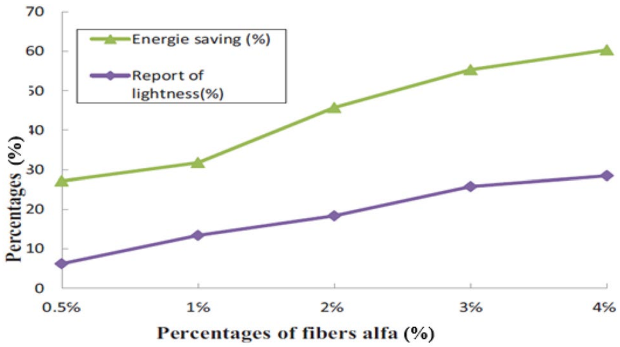


Fig. 12 Energy savings and lightness ratio evolution as a function of Alfa fibre percentages [92]

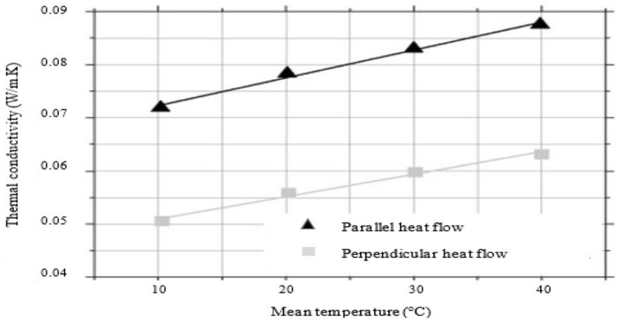


Fig. 14 Straw thermal conductivity with respect to average temperature [102]

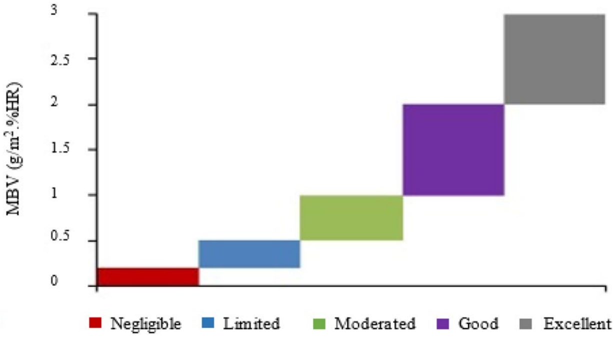


Fig. 15 Classification of the Nordtest project materials with respect to the moisture buffer value [106]

concerned the macrostructure chopped straw and defibrated straw. The thermal conductivity of the defibrated straw was lower than that of the chopped straw. The thermal conductivity of straw, like that of other insulating materials, increases as the temperature and moisture content rises. Straw has a thermal conductivity similar to that of common insulating materials. It has a thermal conductivity of 0.038–0.08 W m^{-1} K^{-1}, which is comparable to other wood fibre insulation materials. To achieve the same thermal insulation efficiency as other more insulating materials such as extruded and extended polystyrene, the thickness of the straw insulation layer should be increased by 30–90% [94]. Many studies have investigated the water vapour transmission properties of straw (Liuzzi et al. [97]; Marques et al. [101]). Water vapour diffusion resistance factor measurements range from 2.59 to 5, while moisture buffering potential (MBV) measurements range from 1.76 to 5.05 g/(m^2. % HR). As a consequence, according to the classification proposed by the NORDTEST project, straw is an excellent moisture regulator (Fig. 15).

An innovative material made by mixing lime, rape straw, and water was developed and studied by Rahim et al. [25, 107]. The authors obtained a thermal conductivity between 0.371 and 0.094 W m^{-1} K^{-1} and a water vapour resistance factor varies from 7.87 to 10.58, which can be explained by the higher open porosity of rapeseed straw concrete. Straw bales are widely used to insulate walls, but they may also be used to insulate roofs and sub-floors. The properties are the same as for wall insulation, and the same precautions must be taken to secure the straw in both cases. Cascone et al. [99] combined compressed straw with a wooden shell called platform frame. It was demonstrated that there was no risk of interstitial condensation forming in the compressed straw wall. The energy performance and environmental assessment of a cross-laminated timber system (XLAM) were then compared. They showed that by using less raw material, the platform frame system with compressed straw has a 12% lower U-value, a higher environmental efficiency, and a higher degree of eco-sustainability over its life cycle. Furthermore, in the summer, straw bale walls provide significant thermal inertia [102, 108].

Some studies have evaluated the advantages of using straw bales for building insulation. Measurements carried out in an innovative and sustainable house built in France have shown that this material helps to minimize heating degrees and energy consumption. The simulated heating requirements in the winter are calculated to be 59 kW h/m^2. In Italy, the energy-saving potential of a straw wall was assessed under various climatic conditions [98]. As compared to the Italian regulations' reference of a Net Zero Energy Building (NZEB), the straw wall performed extremely well in terms of energy efficiency. The embodied energy of a straw wall structure is about half that of a conventional wall assembly, and the corresponding CO_2 emissions are more than 40% lower.

Liuzzi et al. [97] conducted a hygrothermal simulation of a flat using the Wufi® software in two different climatic zones (Bari and Bilbao), assuming a retrofit via interior panels. The materials used were Extended Polystyrene (EPS), Straw Fibre (SF), and Olive Fibre (OF). The simulation was performed in two scenarios: without the panels and with the insulating panels on the inner side of the opaque outer wall. The simulation results show that the annual energy requirement when using SF and OF panels is close to the annual energy requirement for EPS panels in both climates. During the cooling season, however, OF and SF insulation panels perform better, with a reduction of approximately 21% in Bilbao and 14% in Bari.

Cork

Cork (Fig. 16) is a lightweight, reusable, and biodegradable material that is harvested every 9–12 years from the bark of the cork oak (Quercus Suber L.). It has a homogeneous cell structure with thin, regularly arranged cell walls without intercellular spaces. North Africa, as well as parts of Portugal, Spain, and Italy, are home to the cork oak. Cork production

Fig. 16 Cork [111]

in the world is expected to be 201,428 tonnes per year, with approximately 2139942 ha of cork forests [109]. The cork oak occupies 480,000 ha, with a 400,000-ha on Algeria's eastern coast and several massifs totalling 80,000 ha around Algiers and Oran [110]. National production has averaged 9000 tonnes per year over the last decade. After Portugal, Spain, Italy, and Morocco, it is now ranked fifth in the world [52].

Due to its combination of characteristics of lightness, elasticity, impermeability, insulation, wear resistance, fire retardant qualities, hypoallergenic properties, and mould resistance, cork is a material suitable for a variety of construction needs [112]. It has a wide range of uses in this industry, including floor and wall coverings, loft insulation, floor insulation, and roof insulation. Cork used for thermal insulation is usually made from cork oak or recycled cork. It is then either used in bulk or agglomerated in panels, usually as expanded cork. Research on cork is active. It includes various aspects of the material's characterisation, distribution, and application. Several research studies have evaluated the effects of using cork oak materials as thermal insulation in buildings. The thermal conductivity of these materials ranges from 0.036 to 0.065 W m^{-1} K^{-1}, the density varies from 65 to 240 kg/m^3, while the specific heat ranges from 350 to 3370 [54, 113–117]. As shown in Table 4, the thermal conductivity of cork insulators varies depending on the material's state (granular or compact) and density.

With a water vapour diffusion resistance factor of 5–54.61 [29, 113], cork materials have good hydric properties for moisture insulation. Fino et al.[119] investigated the thermal insulation of walls covered with medium density expanded cork panes. To determine the impact of moisture on heat transfer through the cork wall, they conducted a comparative simulation of the insulation's behaviour in winter and summer conditions on the one side, and in dry and wet conditions on the other. The findings clearly demonstrated that moisture absorption during the rainy season is confined to the surface layers and has no effect on the cork's thermal insulation performance. Other research has focused on cork-based composites. The insulation used in the studies by Cherki et al. [120] and Monir et al. [121], is a cork-gypsum composite structure. Its usage would help to improve energy efficiency of buildings. According to this analysis, integrating cork crushes into the gypsum structure decreases the effective thermal conductivity of the latter by more than 70%. Indeed, gypsum has a thermal conductivity of about 0.406 W m^{-1} K^{-1} while the average thermal conductivity of the composite is about 0.11 W m^{-1} K^{-1}.

Table 4 Some characteristics of cork insulation [118]

Type	Density [Kg/m^3]	Thermal conductivity [W m^{-1} K^{-1}]
Bulk cork	70	0.038
Expanded cork panel	120	0.043

Boussetoua et al. [122] developed a new insulating material using cork aggregates and cement. Natural cork aggregates, sand, cement, and water are mixed together to prepare the samples. Different cork-to-sand ratios were considered. The findings indicate that increasing the amount of cork aggregate increases moisture retention, with water buffer values ranging from 0.39 to 1.2 g/(m^2.%HR) and water vapour permeability ranging from 2.7×10^{-12} to 21.4×10^{-12} kg/(m s Pa) as density decreases. Figure 17 shows the standard deviation of the water absorption coefficient and thermal conductivity of cement-cork composites, with the absorption coefficient and conductivity increasing as the cork content decreases. Cork concrete can be used as a thermal insulator, according to these reports.

The thermal efficiency and hygrothermal behaviour of timber frame walls with various external insulation layers were studied by Fu et al. [123]. They observed that expanded cork panels provide better hygrothermal performance and building comfort than an anti-corrosion pine board. Barreca et al. [116] used cork residues and giant reed for panels in buildings in the Mediterranean region. The energy saved by using

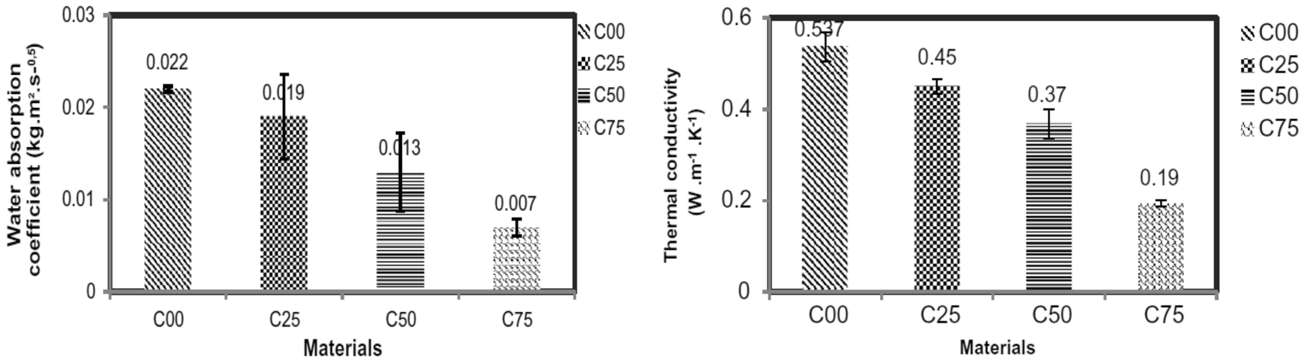


Fig. 17 The standard deviation of the absorption coefficient and thermal conductivity of cork cement composites [122]

agglomerated cork walls for the envelope is more than 75% of the energy spent for the construction with brick walls. Not only is there a financial advantage, but there is also an environmental benefit. Indeed, the estimated annual production of CO2 for heating and cooling of the various houses studied was estimated to be 2517 kg for brick walls, 623 kg for agglomerated cork walls, and 1905 kg for giant reed walls. In addition, Maalouf et al.[124] carried out a one-year hygrothermal simulation of a room for the weather conditions of Constantine in Algeria. According to preliminary findings, cork concrete can reduce energy consumption by about 29% as compared to hollow brick construction. The consideration of Moisture transfer increases energy consumption marginally in the winter due to desorption phenomenon and decreases cooling energy in the summer. El Wardi et al. [125] investigated a new sandwich material using a clay-cork composite as a base material with a protective layer of plaster and cement mortar. Simulations on a small model house in the village of Bensmim in Morocco showed better energy and environmental performance with sandwich panel walls than with conventional hollow earth bricks or Bensmim clay bricks.

Hemp

Hemp has been cultivated since 8000 BC and is the generic name for high-growing varieties of the cannabis sativa plant (Fig. 18). The crop creates excellent economic value for farmers and a steady and sustainable supply of raw materials for various industries, including construction [126], with an excellent dry matter yield of 7–34 metric tons per hectare per year, ease of growth, and high profit margins.

The use of hemp in construction is almost non-existent in Algeria. It is rather used in Europe because of its abundance and its hygrothermal performance in this climate. It is a plant that does not require irrigation, water or fertiliser and its cycle is very short. Today, the hemp plant offers numerous perspectives through its wide applications in several fields. The fibre and the hemp are the most used parts of the plant for the building sector (Fig. 19). The fibres, which represent 29–32% of the straw weight, are used for the production of hemp wool. The shives, which represent 55% of the weight of the straw, are used to create construction products such as mortar, plaster and concrete or can be used directly in bulk. Hemp-based products are transformed by an industrial process or in a workshop and can be applied to any type of construction, in new works or in renovation [127]. The density of hemp fibre varies from 110 to 357 kg/m^3 [25, 30], the exact value depending on the type of particles and the conditions of their development. For hemp wool, on the other hand, it is 35 kg/m^3 [128]. Hemp wool has a high porosity (about 90%) [25], which gives it high thermal performance. Indeed, it has a low thermal conductivity, generally between 0.048 W m^{-1} K^{-1} and 0.058 W m^{-1} K^{-1} [30].

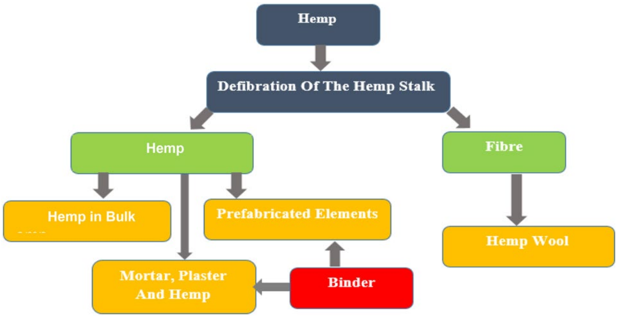


Fig. 19 Example of the use of hemp [129]

Hemp concrete

Hemp concrete, essentially composed of hemp fibres, binder and water, is an innovative and relevant solution in the field of building. It can be used in restoration and renovation as

Fig. 18 Wild-grown hemp (cannabis sativa) plants [126]

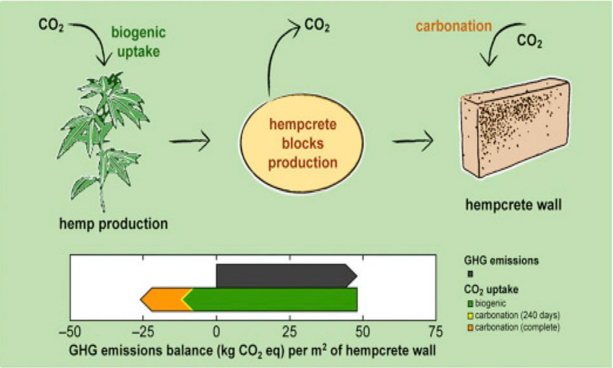


Fig. 20 Illustration of hemp concrete carbon emissions and sequestration, with a net emissions balance indicating carbon negativity [126]

well as in new construction. The most common binder used in combination with hemp shives is lime, it has a lower rate of embodied energy than cement [130]. Furthermore, it can be used for a number of purposes in buildings, including roof, wall, slab, and render insulation, each of which has its own formulation and dosages of the various constituents [30, 131–133] respectively. Hemp concrete's thermal and hydric properties are well-known, and numerous experimental and numerical tests have demonstrated its ability to minimize energy requirements and boost hygrothermal comfort. Hemp concrete (HLC) is a low embodied energy material and an excellent hygrothermal regulator. It has a high silica content, which makes it more resistant to biological degradation than other plant products [134]. Hemp concrete is considered to be carbon negative as the net GHG emissions from its manufacture and installation are in the negative range (Fig. 20). Hemp concrete benefits from a useful process known as carbon sequestration, which refers to a material's ability to store carbon in a stable form within itself [126].

Hemp concrete has a low thermal conductivity, ranging from 0.06 to 0.6 W m^{-1} K^{-1} [130, 133, 135], a total porosity of 68–80% [130, 136] and a density of 200 kg /m^3 to 960 kg/m^3 [133, 137]. Hemp concrete is also an aerated material with high water vapour permeability and its total porosity very close to open porosity allowing it to absorb significant amounts of water [138]. The water vapour diffusion resistance of hemp concrete ranges from 5 to 25 [130, 139]. Furthermore, between 2 and 4.3 g/ (m^2%RH), it is considered an excellent moisture regulator [138, 140]. It can absorb relative humidity when there is a surplus in the living environment and release it when there is a deficit [141–143]. It is important to note that these properties depend on the composition of the material, the type of binder, temperature and humidity. Due to its latent heating effects, which are the results of its high thermal ability and comprehensive moisture control, hemp concrete exhibits phase change material properties [126]. The relationship between relative humidity and the thermal capacity of a hemp concrete wall is depicted in Fig. 21.

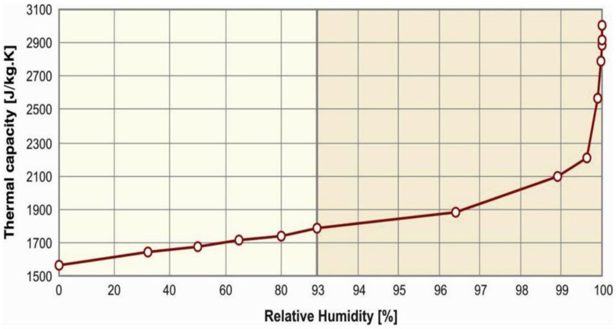


Fig. 21 The Relationship between hemp concrete's relative humidity and thermal capacity [126]

Tran Le et al. [144] used coupled heat and mass transfer to investigate the transient hygrothermal behaviour of a hemp concrete building envelope. The use of hemp concrete resulted in a 45% decrease in energy consumption as compared to aerated concrete. The hygrothermal performance of a hemp-lime building in southwest France was analysed [130]. The measurements show the good thermal inertia of hemp concrete. Indeed, the daily temperature and relative humidity variations have dampened by 90% with 30 cm thick wall. Dlimi et al. [145] investigated the energy efficiency and thickness optimization of hemp wool insulation and air cavity layers in Moroccan building walls. They found that the thickness of the insulation has a significant impact on the multilayer wall's dynamic behaviour. External insulation, on the other hand, necessitates a thin insulation layer, while internal insulation necessitates a thicker insulation layer for better performance. The optimum insulation thicknesses were also discovered to differ depending on the wall's orientation. Moujalled et al. [130] proved that hemp concrete is capable of preventing thermal bridges in structures.

The hygrothermal efficiency of wood-hemp insulation in wood-frame wall panels with and without a vapour barrier was also investigated by Latif et al. [20]. In terms

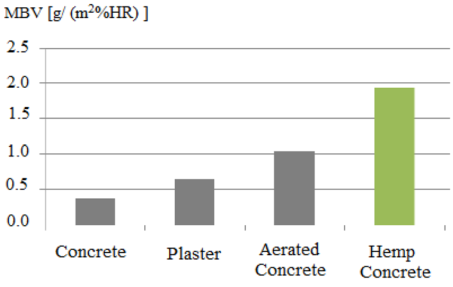


Fig. 22 moisture buffer value (WBV) of common materials and hemp concrete[157]

Table 5 Summary of the overall properties of some bio-based materials

Material	Density [Kg/m3]	Porosity [%]	Capacity thermal mass [J kg^{-1} K^{-1}]	Thermal conductivity [W m^{-1} K^{-1}]	MBV g/(m2.%HR)	Water vapour permeability Kg/(m s Pa)	Factor of resistance to dissemination of steam [-]	References
Plant-based concretes								
Straw concrete	400–560	75.1	1168	0.0371–0.094	2.9–2.59	(1.89–2.56) × 10 − 11	7.87–10.58	[25, 107]
Hemp concrete	200–960	76	1250–2900	0.06–0.6	2.02	10 − 11—10 − 10	5–25	[30, 130, 133, 136, 137, 139, 140]
Linen concrete	598	71	1144	0.168	2.27	2.34 × 10–11	/	[1, 25]
Concrete date palm	680–968	27–64	1500–2341.65	0.091–0.201	1.79–4.05	(2.22–3.59) × 10–11	3.16–8.87	[28, 66, 72, 75] [79, 148]
Wooden concrete	1090–1294.89	/	952.65–1035.8	0.31–0.42	1.96–2.55	2.19 × 10–12	36	[51]
Cork concrete	908.1–1937.7	/	/	0.5–0.194	0.39–1.2	2,7 × 10–12-21.4 × 10–12	9.4–71.9	[122]
Insulation panels								
Wood-lime panels	875.62–984.31	1.33–1.4	/	0.0742–0.1078	/	/	509.9–1868	[56]
Wood fibre panels	150–320	89–97	1700–2000	0.04–0.053	2–3,5	/	2.6–16.8	[55, 56, 149, 150]
Solid wood	368–580	67	1280–1500	0.080–0.192	/	/	17–160.9	[149], [54]
OSB	560–620	/	1320–2100	0.092–0.13	0.87–2	/	42–812.8	[26, 55, 56, 151]
Expanded cork	65–240	19–86	1600–2100	0,037–0,044	/	/	5–54.61	[113, 115, 123, 152]
Bamboo panels	538	63.17	1760	0.088	3.9	1.77 × 10–11	13.1	[153, 154]
Loose fill insulation (fibrous insulation)								
Wood fibre	50–270	/	1900–2100	0.038–0.050	/	/	1–5	[53]
Straw	63–350	83.05–91	1075–3850	0.038–0.08	1.76–5.05	/	2.59–5	[98, 99, 101]
Hemp wool	35	95	1200	0.04	/	/	3.7	[128, 155]
Wood wool	47	/	1330	0.041	/	/	3.6	[156]

Table 6 Some advantage/disadvantage and application area of presented materials

Materials	Areas of application	Advantage	Disadvantage
Plant-based concretes	– Wall construction (filling walls with framework); – Lining of existing walls: projection or prefabricated blocks; – Insulation of floors and roofs; – Plaster with insulating character	– Lightweight concrete; – Excellent thermal and acoustic insulation properties; – Their ability to regulate humidity provides a comfort advantage in the home	– Mechanical performance of the products is generally low; – The vegetable particles are intrinsically weak mechanical resistances, and certain substances which they contain (sugars) slow down, even inhibit the setting of the hydraulic binder
Insulation panels	– Internal insulation of walls, partitions, roofs and floors; – External insulation of walls under plaster or cladding and roofs	– Materials with good thermal and acoustic performance; – They also contribute to the storage of atmospheric carbon and the preservation of natural resources; – They therefore require little transport	– Materials that are sensitive to fungi and moulds. These products are therefore subject to chemical treatments; – Particular care must be taken when laying them, because despite the treatment, they must not be in contact with a too humid environment; – Some materials must be wrapped in a membrane that will isolate them from other materials and thus protect them
Loose fill insulation	– Interior insulation of walls, attics and roofs; – Insulation of unfinished attics by horizontal removal on existing floors or between joists; – Prefabrication possible in wooden boxes attached to a structure	– Blown-in insulation is more efficient than roll or board insulation; – Every corner of your attic is covered, – Requires less handling, and is faster to install than traditional insulation	– Bulk bio-based materials may require chemical treatment against mould or insect attack and their blowing method generates dust

Table 7 The U-thermal transmission of exterior walls with natural insulation of buildings

Description of the walls	The layers of the wall (from the outside in)	Thicknesses mm)	U_{tot} (W/m ^{2} K)	Reference
Straw bale wall	Cocciopesto plaster	31	0.154	[98]
	Fir wood	21		
	Straw bales	350		
	Fir wood	21		
	Air gap	50		
	Fir wood	21		
	Raw earth plaster	29		
Hemp wood wall	Wooden rainscreen	10	0.29	[20]
	Air gap	25		
	Breather membrane	0.5		
	OSB panel	11		
	Wood-hemp insulation	100		
	OSB panel	11		
Multi-layered wall with external insulation made of insulating cork board	Insulating cork panel	40	0.275	[123]
	Sealing membrane	2		
	OSB panel	12		
	Glass cotton insulation	89		
	Spruce-pine—fir SPF	89		
	OSB panel	12		
Cellulose fibre reinforced concrete wall (CFRC)	CFRC panel	40	0.2142	[158]
	Sprayed polyurethane	60		
	Lightweight concrete panel	50		
	EPS 2 (polystyrene)	90		
	Gypsum board	9.5		
Hemp concrete wall	Lime sand plaster	10	0.26	[159]
	Sprayed hemp concrete	36		
	Lime-sand plaster	10		
	Hemp-lime plaster	10		
Agglomerated cork wall	Agglomerated cork board	60	0.279	[116]
	Air gap	30		
	OSB panel	10		
	Air gap	30		
	Agglomerated cork board	60		
Brick wall	Brick	200	2.450	[116]
	Plaster	10		
Concrete block wall with polystyrene insulation	Concrete blocks	220	0.35	[102]
	Polystyrene	100		

of moisture control, when gypsum board was used as an inner lining in the vapour open wall panel, the rate of wetting and drying was faster in the insulation interface. For the wood-hemp insulation in the wallboard, the hygrothermal condition at the expanded cork board insulation interface of the wallboard without a vapour barrier was more favourable for mould spore germination than that of the wallboard with a vapour barrier. Dhakal et al. [141] conducted a hygrothermal study of two hemp walls, one with lime rendering on the outside and inside and the other with ventilated wood cladding. The ventilated rainscreen device performed significantly better in terms of moisture control, according to the findings. As a result, this device might be a better choice for hemp concrete wall assembly in humid and temperate climates. Another experimental study comparing the hygrothermal properties of hemp and

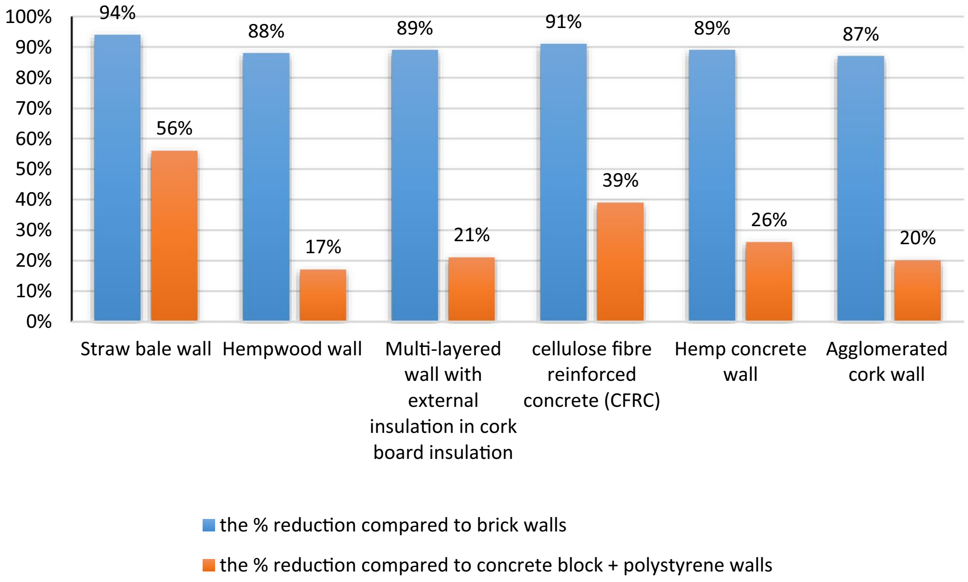


Fig. 23 Percentage reduction in thermal transmittance compared to conventional walls

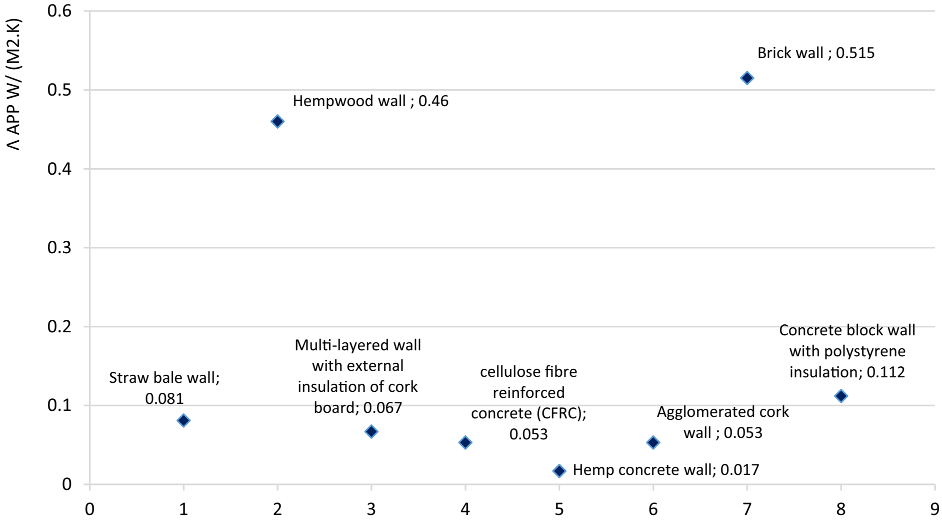


Fig. 24 The apparent thermal conductivity for different wall configurations

rock wool found that hemp had a lower frequency and probability of condensation than rock wool [146, 147].

Comparative analysis of the hygrothermal performance of eco-materials

Table 5 summarises the results of the hygrothermal properties of the materials presented in this research from the literature. Thermal properties such as thermal conductivity and heat capacity were evaluated for both steady state and dynamic conditions. Hydric properties were examined, including moisture buffer values, water vapour permeability, and water vapour resistance. The majority of the materials presented are made of fibres or granules and can be considered as porous materials with interconnected cavities. Colours were used to highlight the thermal and water characteristics of these materials. Green denotes materials that perform well, while yellow denotes materials with average performance.

The main technical advantage/disadvantage as well as the areas of application of the different bio-based materials presented are summarized in Table 6

Comparative analysis

A simple reading of the tables shows that most of the biobased materials found in the literature have good thermal and water properties. Plant fibres alone show better performance compared to cases where they are incorporated in binders. The lowest thermal conductivity value (0.038 W m^{-1} K^{-1}) was measured for straw with a density of 63–350 kg/ m^3 followed by hemp wool, wood wool and wood fibre boards. These materials generally have a porosity of over 65% which allows for the possibility of coupled heat and moisture transfer within these materials. Straw concrete was found to have the best thermal conductivity and is also resistant to water vapour as it has a permeability of 1.89×10^{-11} kg/(m s Pa). According to Table 5, the water buffer value measured on bio-based materials shows that these materials are very good water regulators. This characteristic varies from one material to another depending on the binder and the fibre used. Indeed, for wood and bamboo panels, it is found that they have higher MBV values than OSB. However, concretes based on plant aggregates are excellent moisture regulators with a buffer capacity of more than 3 [g/m^2. % RH]. Hemp concrete is by far the best moisture regulator (Fig. 22) [157].

We compared the U-thermal transmission of exterior walls with natural insulation of buildings in different countries with that of an uninsulated brick wall and another concrete block wall with polystyrene insulation, considered as benchmark walls. Table 7 summarises the results obtained. The total transmittances of the composed walls presented were calculated considering the effective thickness of each material to obtain the desired resistances and fulfilling the requirements of the code of each country.

It can be seen that the reference walls have the highest transmission coefficients. These values are reduced by about 17–94% for the different walls with natural insulation (Fig. 23).

The U-value depends strongly on the thickness of the wall. Therefore, the use of apparent thermal conductivity is proposed to compare the performance of walls. The apparent thermal conductivity λapp is the U-value multiplied by the wall thickness e: λapp = Uxe. As the thickness of a wall increases, so does its thermal performance. Figure 24 presents the apparent thermal conductivities of walls calculated from the results in Table 6.

It can be clearly seen that external walls with natural insulation have lower apparent conductivities than brick and concrete block walls. The most efficient configuration is the hemp concrete wall which has an apparent conductivity 6 times lower than the concrete block wall and 30 times lower than the brick wall. This comparison shows how natural and renewable materials can be used to meet current requirements. For indoor air conditioning and building comfort, their application allows for considerable energy savings and, as a result, lower CO_2 emissions into the atmosphere.

Conclusion

This paper addressed a state of the art in natural and sustainable insulating materials used in the construction sector. This synthesis also provides an overview of research on the international energy context, the thermo-hydric behaviour of bio-based materials and hygroscopic envelopes. We may infer from this research that materials produced from plant particles and fibres are an appropriate solution to current environmental issues. The use of more environmentally friendly buildings presents opportunities for the development of new sustainable materials. Several studies have looked into the thermal, water, and environmental efficiency of eco-materials that are not commonly used in construction right now. Natural sources, such as residues from food production, manufacturing industries, or recycled goods, may be used to create these non-conventional materials.

Comparative analyses were carried out taking into account the thermal properties for several wall configurations, the most promising and best performing materials are eco-materials, external walls with natural insulation show considerable thermal performance. Wood-based envelopes were the most widely studied. In terms of plant-based concretes, hemp concrete envelopes were the most well documented. The characterisation of the thermohydraulic behaviour of hygroscopic envelopes is carried out at three scales: material, component and building. These materials, because of their hygroscopic nature, are subject to a variety of heat transfer and moisture fixation phenomena, but they also have a heterogeneous composition, making it difficult to determine their thermophysical properties. Eco-materials (grass, date palm wood, Alfa plant, straw, cork, hemp, plant concrete) have been shown to act as moisture moderators, improving hygrothermal comfort, energy consumption, and indoor air quality.

Declarations

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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