



**HAL**  
open science

# A review on the properties of straw insulation for buildings

Yaping Zhou, Abdelkrim Trabelsi, Mohamed El Mankibi

► **To cite this version:**

Yaping Zhou, Abdelkrim Trabelsi, Mohamed El Mankibi. A review on the properties of straw insulation for buildings. *Construction and Building Materials*, 2022, 330, pp.127215. 10.1016/j.conbuildmat.2022.127215 . hal-03899231

**HAL Id: hal-03899231**

**<https://hal.science/hal-03899231v1>**

Submitted on 22 Jul 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# A review on the properties of straw insulation for buildings

Yaping Zhou <sup>a,\*</sup>, Abdelkrim Trabelsi <sup>b</sup>, Mohamed El Mankibi <sup>a</sup>

<sup>a</sup> Univ Lyon, LTDS, ENTPE, UMR5513, 69120 Vaulx-en-Velin, France

<sup>b</sup> Univ Lyon, UCBL, INSA Lyon, CNRS, CETHIL, UMR5008, 69622 Villeurbanne, France

\*Corresponding author.

E-mail address: [yaping.zhou@entpe.fr](mailto:yaping.zhou@entpe.fr) (YP. Zhou)

**Abstract:** Applying thermal insulation in building envelope is a promising approach for energy efficient building. The mainstream thermal insulation products are however produced from petrochemicals causing high energy consumption and adverse effect on environment during their production as well as arising reuse and recycle issues. Insulation materials derived from local agricultural straws have attracted increasing attention due to their superior hygrothermal performance, low life cycle cost and low carbon footprint. This paper aims to provide a comprehensive review on the two categories of straw insulation products, i.e., straw bales and straw composites. In particular, available researches on the properties including thermal insulation, moisture, mechanical, durability and fire resistance are thoroughly reviewed and discussed with the consideration of different factors. In addition, the existing literature on the life cycle assessment of straw wall by comparison with tradition wall is presented.

**Keywords:** Thermal insulation, straw bale, straw composite, moisture properties, mechanical properties, life cycle assessment

## 1. Introduction

In recent years, promoting energy efficiency attracts increasing attention with growing concerns on the energy crisis and global warming. Buildings, accounting for approximately

20-60% of total energy consumption in different regions of the world [1, 2], play a major role in improving energy efficiency. In the major urban buildings, heating and cooling consume over 40% of total energy consumption [3, 4]. Applying appropriate insulation materials and technologies to building envelop is regarded as a promising approach to guarantee indoor comfort with less dependence on heating and cooling systems.

Thermal insulation materials aim to retard the heat flow by conduction, convection and radiation. The most significant factor that characterizes the effectiveness of a thermal insulation material is its thermal conductivity. The lower thermal conductivity of a material, the increased effectiveness it is as a thermal insulation, and consequently a thinner layer is required to provide an equal interior temperature. Nowadays, the mainstream thermal insulation products are manufactured from synthetic materials, such as glass fiber, mineral wool and plastics due to their predominate thermal properties [5]. However, their production consumes a large amount of non-renewable resource and causes greenhouse gas emission, which ultimately lead to climate change and environment pollution. Also, they are generally not subjected to biological degradation. Therefore, a topic of major interest in building construction sector is to replace conventional insulation materials with natural insulation materials, which exert low environment impact during their entire life cycle. It has been estimated that utilizing cellulose fiber insulation to substitute the common insulation materials (i.e., rock wool and glass wool) in buildings allows to reduce 39% of fossil fuels and 6-8% of CO<sub>2</sub> emissions [6].

Straw is a residue from harvesting crops, such as wheat, rice, barley, oat, corn, rye and rape. A large quantity of billion tons is produced every year around the world [7]. The treatment of straw is a largely disputed problem as a large fraction of straw is deposited by incineration and landfill except for the on-farm end uses such as animal bedding and feeding. Incineration of straw has negative effects, such as the toxicity, greenhouse gases emission and air pollution, and thus is banned in European Union countries. Mixing straw with soil generates methane during the straw's anaerobic decomposition, resulting in a higher global potential compared to the incineration [8]. Conversion straw waste to biobased products for buildings provide a cost-effective and eco-friendly approach to solve these issues. For a long

time, straw has been used for insulation purposes with low density and low thermal conductivity due to its hollow internal structure. Zhao et al [9] reported that the insulation material derived from agricultural straw has a life cycle cost of 150 RMB/m<sup>2</sup> for 25 years span, which is lower than the insulation materials from municipal solid waste, industrial solid waste and traditional insulation materials including extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PU), phenol-foam (PF), perlite, rock wool and glass wool.

This paper aims to provide a review of the available information on straw insulation for buildings. First, the characterization methods and standards of properties including thermal insulation, moisture, mechanical, durability and fire resistance are summarized. Second, the general context on straw including microstructure and chemical composition is presented, which are followed as the introduction of two categories of straw insulation products, i.e., straw bale and straw composite. Third, the available researches on the properties including thermal insulation, moisture, mechanical, durability and fire resistance are thoroughly reviewed and discussed with the consideration of different factors, such as density and fiber size. In addition, the existing literature on the life cycle assessment of straw wall by comparison with tradition wall are presented. Finally, this paper is concluded with a summary of the findings and contributions and is outlined the open issues to be addressed.

## **2. Characterization of thermal insulation**

### **2.1. Thermal insulation properties**

The main intrinsic properties of insulation materials regarding thermal insulation performance are thermal conductivity for steady state conditions, heat capacity, thermal diffusivity, thermal effusivity involved in transient conditions. The thermal conductivity of a material describes its ability of conduct heat, while the specific heat capacity measures the ability of store heat. A high specific heat capacity allows to delay the indoor temperature increase or decrease. Both the thermal diffusivity and thermal effusivity consider the ability to exchange and store heat. The thermal diffusivity measures the rate of heat transfer through a material, while the thermal effusivity measures the rate of heat absorption within a material under dynamic environment conditions. The thermal diffusivity can be expressed as the ratio

of thermal conductivity to the product of density and specific heat capacity, and the thermal effusivity can be expressed as the square root of the product of density, thermal conductivity and heat capacity.

## 2.2. Moisture properties

Moisture inside a building material can affect heat flux, heat capacity, condensation, mold growth and structural integrity. Hygric properties are also indispensable parameters for modelling and analysis of the hygrothermal performance of the materials in building envelopes. The key hygric properties includes sorption isotherms, water vapor permeability, moisture buffering value and water absorption coefficient. The sorption isotherms of a material measure its moisture storage ability, which can be defined as the moisture content at equilibrium states when subjected to a series of relative humidity. The water vapor permeability of a material measures its ability of moisture transport for steady state conditions, which can be defined as the rate in which water vapor is transported. Water vapor resistance factor is a dimensionless parameter to represent the water vapor permeability of a material in comparison to an air layer with the same thickness. Moisture buffering value (MBV) of a material measures its ability to moderate variations in relative humidity when it is exposed to dynamic humidity conditions, which can be defined as the amount of water vapor uptake or release through unit exposed surface area when subjected to cyclic variations of relative humidity.

## 2.3. Mechanical properties

Mechanical properties are essential to evaluate the behavior and the performance of a building material when it undergo various types of stresses. The strength of a building material mainly includes compressive strength, tensile strength and flexural strength. The compressive strength of a material can be defined as the capacity to withstand loads before failure. The tensile strength and the internal bonding strength of a material measure its resistance to lengthwise stress by performing tensile test in parallel and perpendicular direction to faces, respectively. The flexural strength (also called as bend strength and modulus of rupture) of a material measures its ability to resist loading applied perpendicular

to its longitudinal axis, which is typically determined from a three-point loading test. Table 1 summarizes the established international or national standards for measuring the thermal insulation, moisture and mechanical properties.

Table 1 Standard evaluation method for thermal insulation, moisture and mechanical properties

Parameter	Symbol	Unit	Standard	Ref
Thermal conductivity	$\lambda$	W/(m·K)	EN 12664	[10]
			EN 12667	[11]
			EN 12939	[12]
			ASTM C518	[13]
Specific heat capacity	$C_p$	J/(kg·K)	ISO 11357	[14]
Thermal diffusivity	$\alpha$	m <sup>2</sup> /s	ISO 22007	[15]
Thermal effusivity	$e$	W·s <sup>1/2</sup> /m <sup>2</sup> /K	ASTM D7984 - 16	[16]
Sorption isotherms	$w$	kg/m <sup>3</sup>	EN 12571	[17]
Water vapor diffusion resistance factor	$\mu$	-	EN 12086	[18]
			EN 12572	[19]
Moisture buffering value	$MBV$	g/ $\Delta$ RH/m <sup>2</sup>	JIS A 1470-1	[20]
			NDRDTST protocol	[21]
			ISO 24353	[22]
Water absorption	$W_p$	kg/m <sup>2</sup>	EN 1609	[23]
			EN 29767	[24]
	$WA$	%	EN 12087	[25]
Compression strength		MPa	EN 826	[26]
Tensile strength		MPa	EN 1608	[27]
Internal bonding strength	$IB$	MPa	EN 1607	[28]
Flexural/bending strength/modulus of rupture		MPa	EN 12089	[29]

#### 2.4. Durability

The durability of an insulation material is crucial to guarantee potential energy saving in long term and service life of buildings. Accelerated ageing test, i.e., exposing materials to extreme environment conditions, is commonly conducted to evaluate the durability of a material as it can save much time. Due to the organic structure of straw insulation, the mold growth is one of the important parameters to characterize its durability as the mold plays a key role in straw degradation, making a compromise in materials' integrity and performance [30]. Different methods and standards are proposed to evaluate the resistance to mold growth,

such as Johansson method [31], AWPA standard E24-06 [32], ASTM 2012 [33] and EN ISO 846 [34].

## 2.5. Fire resistance

The fire resistance of a building material is related to safety issues. According to the standard EN 13501-1, insulation materials can be classified to six grades from A representing incombustible to F representing highly combustible [35]. Different parameters are used to evaluate the fire resistance of materials including ignition, flame spread, mass loss rate, heat release and smoke production. The most typical flammability tests employed for insulation materials are cone calorimetry, pyrolysis combustion flow calorimetry (PCFC) and limiting oxygen index (LOI), as shown in Table 2. Another commonly used method is thermal analysis in small scale, including differential scanning calorimetry (DSC) and thermalgravimetric (TGA), in order to understand the response of different materials under fire circumstances.

Table 2 Standard evaluation methods for fire resistance

Flammability test	Objective	Standard	Ref
Cone calorimetry	Mimic the penetrative burning into medium sized materials	ISO 5660-1	[36]
		ASTM E 1354	[37]
Pyrolysis combustion flow calorimetry	Pyrolysis and combustion of materials in small scale (several milligrams of samples)	ASTM D7309	[38]
Limiting oxygen index	Ignition resistance by measuring the minimal oxygen concentration supporting combustion	ISO 4589	[39]
		ASTM D2863	[33]
		NF T 51-071	[23]

## 3. Straw context and thermal insulation products from straw

### 3.1. Composition and microstructure of straw

Straw is an agricultural by-product consisting of the dry stems or stalks of cereal plants, which is remained in the field after grain and chaff have been removed. The major structural components are cellulose, hemicelluloses and lignin [40]. Cellulose is a linear homopolymer

with a partially crystalline structure that ensures strength and resistance to hydrolysis, while hemicellulose is an amorphous linear heteropolymer with little strength. Lignin has a complex three-dimensional structure that connects cellulose and hemicellulose, providing an impermeable cover in plant cell walls, enabling water resistance and strength to the cell wall. Other natural substances also exist in straw, such as water-soluble extractives, wax and ash. Thermal degradation behaviors of a material are strongly correlated to its components. Titiloye et al. [41] studied the thermal degradation characteristics of agricultural wastes including corn straw, corn cob, rice straw, rice husk etc. In their study, the TGA results showed that most of the weight lost occurred at the temperature between 250 °C and 450 °C. Moreover, the corn straw had the highest weight loss of 70% and the rice straw had the lowest weight loss of 45%. This is due to the low ash content within corn straw and unusual high ash content within rice straw (see Table 3).

Straw is a porous material with multi-layer structure, which is generally referred as a hygroscopic material [42]. The porous nature enables the material to exchange water vapor with surrounding humid air, regulate fluctuations in relative humidity and thus improve indoor comfort [43]. The scanning electron microscopic (SEM) image of the cross section of wheat straw ( see Fig. 1) [44] shows a concentric ring with a lumen portion in the center surrounded by porous structures. The epidermis in the outermost ring of stem is a dense layer with wax, ash and other inorganic substances that guarantees the mechanical strength and evaporation inhibition, and beneath epidermis is a loose layer, which is composed of parenchyma and vascular bundles. The microstructure of straw can vary due to different species and plant growth environment. Fig. 2 shows a comparison of the cross section between wheat straw and rice straw by using a scanning electronic microscopy [45], where the wheat straw has larger cells with larger variability in size and smoother surface than that of rice straw.

Table 3 Composition of different types of straw (% dry matter) [46, 47]

Straw type	Cellulose	Hemicellulose	Lignin	Water-soluble	Wax	Ash
Wheat	38.6	32.6	14.1	4.7	1.7	5.9
Rice	36.5	27.7	12.3	6.1	3.8	13.3



Barley	34.8	27.9	14.6	6.8	1.9	5.7
Oat	38.5	31.7	16.8	4.6	2.2	6.1
Corn	38.5	28.7	15	5.6	3.6	4.2
Rye	37.9	32.8	17.6	4.1	2.0	3.0
Rape	37.6	31.4	21.3	-	3.8	6.0

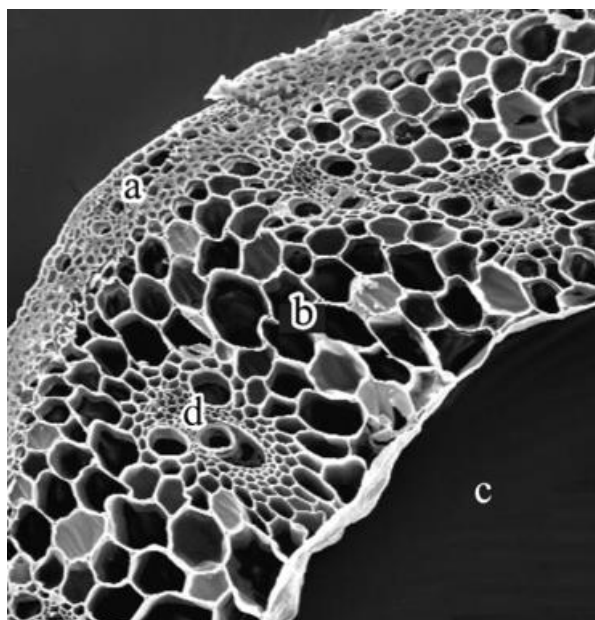


Fig. 1. Cross section of wheat straw (a) epidermis, (b) parenchyma, (c) lumen, (d) vascular bundles [44]

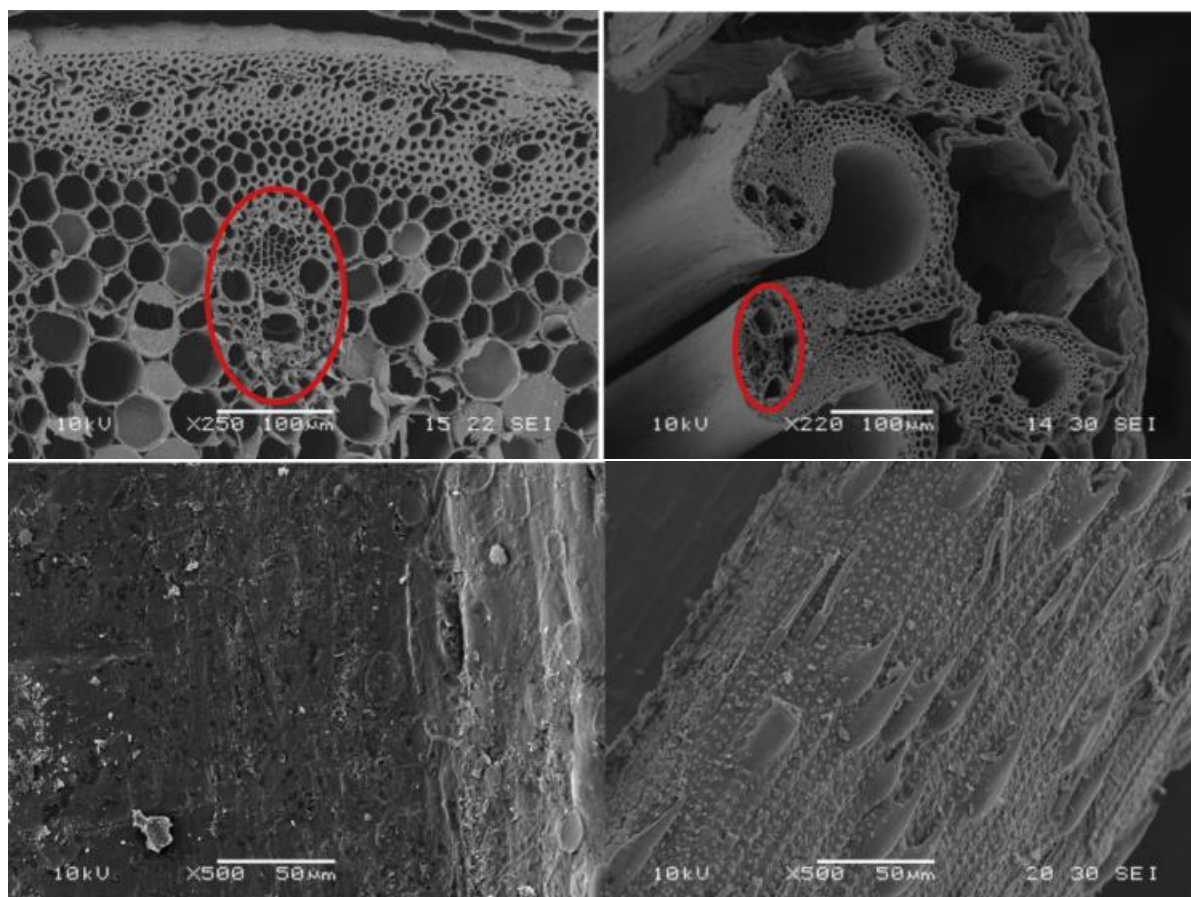


Fig. 2. Cross section (above) and external surface (below) of wheat straw (left) and rice straw (right) [45]

### 3.2. Straw bale and straw composite

For the application in building construction, straw bale has been functionalized as load bearing or infilled insulation materials. It is produced directly from the deposited straw wastes in the field after harvesting crops. Baling machines are used to collect, compress and tie the straw wastes into compacted bales with steel or polypropylene twines. Through the baling process, a large range of density values can be produced and the orientation of the straw fibers within the bales can also be affected. For the application in construction and buildings, the straw bales are commonly laid flat with dimensions of 900 mm to 1000 mm length, 450 mm width and 350 mm to 375 mm high [48].

Another type of straw insulation attracting attention is straw composite, in which the straw fibers are usually molded with alternative binders, including biocomponent fibers, inorganic materials, synthetic resins and natural adhesives. A typical technology of production of straw composite is as follows: (1) process the straw by methods such as cutting, smashing, crushing or milling to obtain short straw fibers in order to avoid the mixing difficulties in using their initial size [49]; (2) pneumatic, mechanically or manually mix straw fibers with binders and alternative functional materials; (3) formation of insulation panel/board, which is followed by a compressing step, such as pressing [50, 51], thermal pressing [52, 53] and high-frequency hot pressing [54, 55]) to achieve desired shape, stability and density; (4) dry or cure the panel/board in room condition or oven to accelerate the process.

## 4. Properties of straw bales

### 4.1. Thermal insulation properties

Various studies have reported a range of thermal conductivity values from 0.03 W/(m·K) to 0.1 W/(m·K) for straw bales, as shown in Table 4. The variability can be caused by, for example, the types of straw, the bale density, the orientation to heat flow, the ambient temperature and relative humidity. According to work of [56], a negligible variation was

observed between wheat straw bales and barley straw bales. Fig. 3 presents the thermal conductivity versus the density of straw bales as found in various studies. In the work of [57-60], a linear correlation was observed, where thermal conductivity generally increased with density, while in the work of [61-63], the thermal conductivity was relatively independent of density. Additionally, according to the work of [64], the lowest thermal conductivity values were obtained in bale densities ranging from 60 kg/m<sup>3</sup> to 80 kg/m<sup>3</sup>, and densities not in that range exhibited higher thermal conductivity.

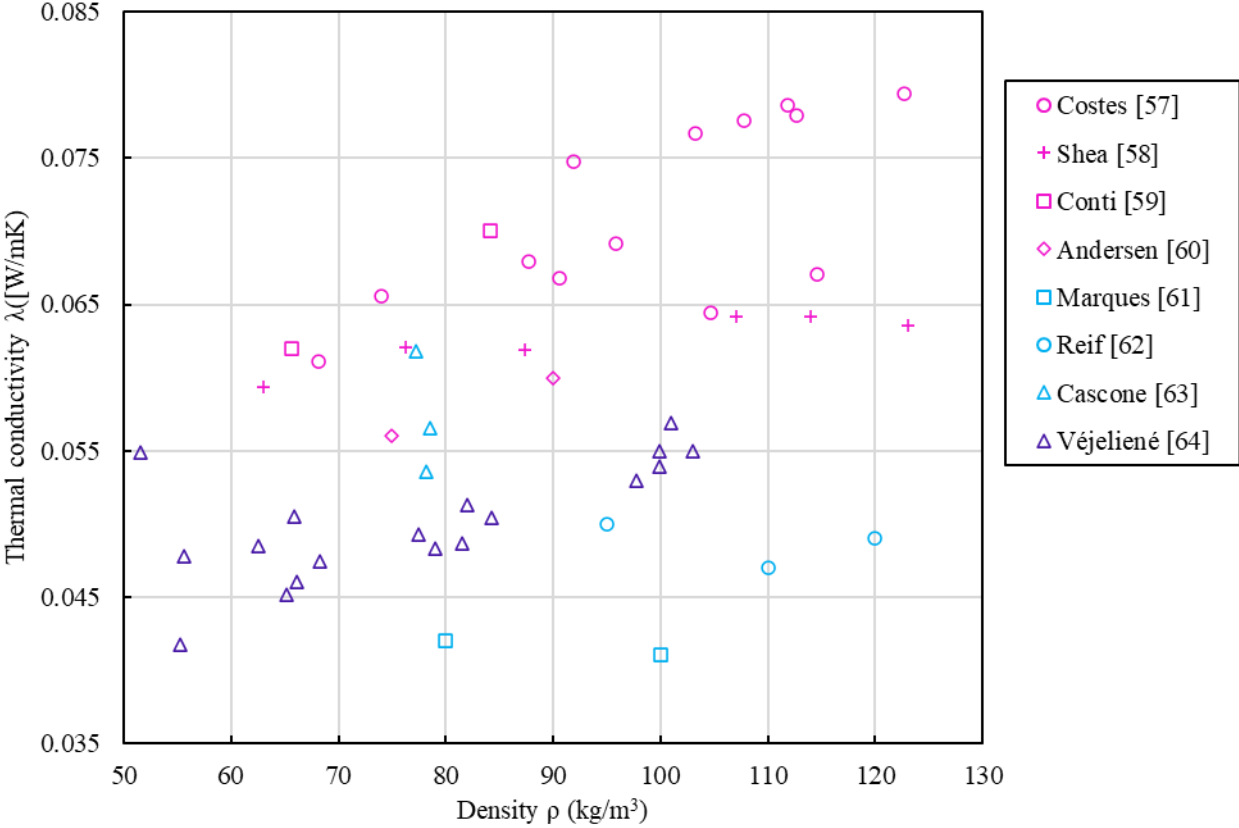


Fig. 3. Thermal conductivity versus density based on the studies from Costes [57] , Shea [58], Conti [59], Andersen [60], Marques [61], Reif [62], Cascone [63], Véjeliéné [64]

The thermal conductivity of straw bales was highly influenced by their orientation to heat flow, with the lowest thermal conductivity value of parallel and perpendicular oriented straw differing about 1.8 times reported by Véjeliéné et. al [65]. Fig. 4 gives the box plot of thermal conductivity values for the parallel, perpendicular and not specified orientations from various studies. It can be seen that the

perpendicular orientation always showed the lowest thermal conductivity values from minimum, maximum, median, first quartile and third quartiles, indicating the perpendicular orientation is preferable to improve thermal performance in buildings. Platt et. al [48] developed a laboratory scale baler and baling process to orientate the straw preferentially, and found that changing the parallel orientation to perpendicular orientation decreased the thermal conductivity by 28% (from 0.078 to 0.056 W/(m·K)).

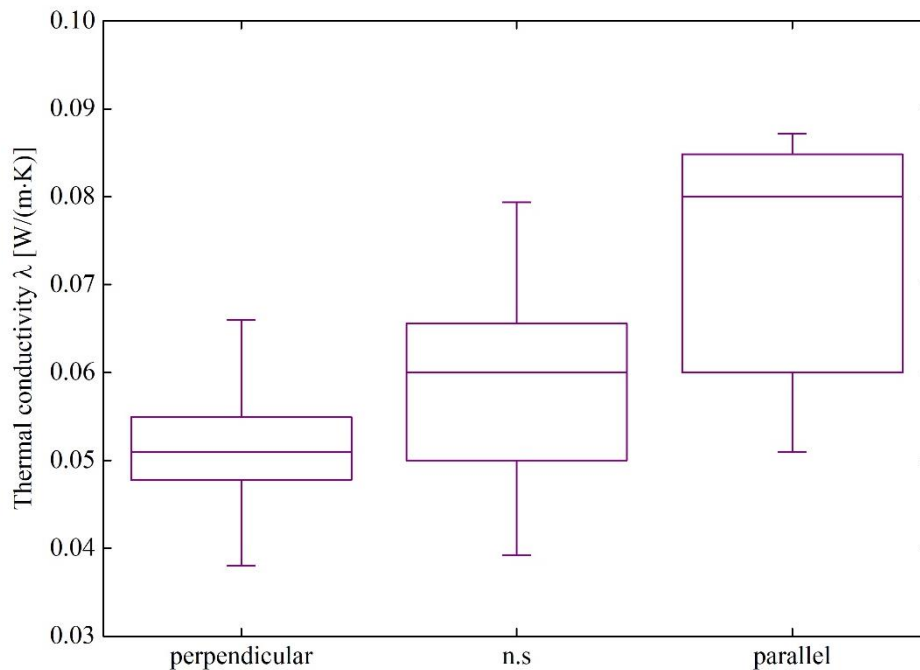


Fig. 4. Box plot of thermal conductivity for different bale orientation based on studies from Table 4

Generally, the thermal conductivity of straw bales lineally increased with the increase of ambient temperature and internal moisture content. Douzane et.al [66] investigated the effect of temperature on the thermal conductivity of both the parallel and perpendicular orientated straw bales by applying guarded hot plate. In their study, a linear correlation between the thermal conductivity and mean temperature ranging from 10 °C to 40 °C was obtained as:

$$\lambda = \lambda_0 (1 + aT)$$

Where T represents the mean temperature,  $\lambda_0$  represents the thermal conductivity of straw bales at 0 °C, and a represents the experiment coefficient, for parallel oriented straw bales:  $\lambda_0$  equals to 0.067 with a equaling to 0.0078, and for perpendicular orientated straw bales:  $\lambda_0$

equals to 0.046 with a equaling 0.009.

Cascone et.al [63] determined an exponential function to describe the correlation between the thermal conductivity and temperature of straw bales by using a heat flow apparatus. The mean temperature ranged from 25 °C to 35 °C, and the function after curve fitting was expressed as:

$$\lambda = 0.0534e^{(0.0026T)}$$

According to the work of [67], the thermal conductivity of straw bales at dry state was increased by 20% when they were conditioned at 80% RH and 23 °C and reached moisture content equilibrium. The only research that simultaneously consider the influence of multiple variables on the thermal conductivity and thermal diffusivity of straw bales was done by Sabapath et.al [68]. In their study, the effect of bale density, bale orientation, ambient temperature and relative humidity were taken into account. Specifically, samples were prepared in different densities ranging from 50 to 95 kg/m<sup>3</sup> and three orientations, i.e., perpendicular, random and parallel. The thermal conductivity and thermal diffusivity values of these samples were measured by a transient plane method at temperature of 25-45 °C and at relative humidity of 0-80% RH. The orientation was found to have the largest impact on both the thermal conductivity and thermal diffusivity among all the variables. Additionally, the random and perpendicular oriented samples exhibited similar thermal insulation properties and followed similar trends with variable variations to some extent, while the parallel samples exhibited obvious difference. For example, an increase of 1.5 times in thermal conductivity values was found for random and perpendicular orientation, whereas that of 2.5 times for parallel orientation when they were conditioned at high humid case of 80% RH compared to the dry state. Moreover, two polynomial functions were determined for parallel and random/perpendicular oriented respectively:

$$\lambda_{\text{parallel}} = -0.0103\rho^2 + 2.196\rho + 1.573(\%RH) + 0.478 T - 46.072 \text{ [mW/mK]}$$

$$\lambda_{\text{random/perpendicular}} = -0.00002\rho^2 + 0.317\rho + 0.375(\%RH) - 0.042T + 30.794 \text{ [mW/mK]}$$

Table 4 Thermal conductivity of straw bales as found in literature published by various authors

Year	Authors	Straw type	Density (kg/m <sup>3</sup> )	Mean temperature (°C)	Moisture content MC /Relative humidity RH (%)	Fiber orientation	Measuring instruments	Thermal conductivity (W/m•K)	Ref
2021	Mehravar et al.	Wheat	61	10	-	-	Heat flow meter	0.047	[69]
2020	Cornaro et al.	-	106	-	-	Perpendicular	-	0.066	[70]
2019	Marques et al.	Rice	80-100	10	0	-		0.039	[61]
					RH 50%			0.041-0.042	
					RH 80%			0.045-0.048	
2019	Sabapathy et al.	Rice	68	30	0	Parallel	Transient plane source	0.08	[68]
						Perpendicular		0.057	
						Random		0.049	
					RH 40%	Parallel		0.134	
						Perpendicular		0.059	
						Random		0.06	
					RH 60%	Parallel		0.165	
						Perpendicular		0.078	
						Random		0.075	
					RH 80%	Parallel		0.182	
						Perpendicular		0.084	
						Random		0.07	
2019	Cascone et al.	Wheat	78	20-35	MC 8%	Random	Heat flow meter	0.056-0.058	[63]
2017	Costes et al.	-	68-123	10	RH 50%	-	Hot plate	0.061-0.079	[57]
2017	D'Alessandro et al.	-	80	22	RH 45%	Parallel	Hot plate	0.051	[71]
	Munch-Andersen et al.	-	62-150	-	-	Parallel		0.057-0.082	

		-	75-150	-	-	Perpendicular		0.038-0.057	
2016	Douzane et al.	-	80	10-40	-	Parallel	Hot plate	0.072-0.088	[66]
		-	-	-	-	Perpendicular		0.05-0.063	
2016	Conti et al.	Triticosecale	66-84	19	MC 12%	-	Hot box	0.062-0.07	[59]
2016	Reif et al.	Wheat	95-120	-	0	-	-	0.045-0.046	[62]
					RH 50%			0.047-0.05	
					RH 80%			0.057-0.059	
2015	Volf et al.	-	98	-	-	-		0.065	[72]
2012	Shea et al.	Wheat	63-123	10	RH 50%	Random	Hot box	0.059-0.064	[58]
2011	Vėjelienė et al.	Barley	63-121	-	-	Parallel	Hot plate	0.085-0.087	[64]
			50-103			Perpendicular		0.042-0.057	
2005	Goodhew and Griffiths	-	60	-	-	-	Thermal probe	0.067	[73]
2003	Ashour et al.	Barley	69-98	10-32	-	-	-	0.03-0.094	[74]
		Wheat	82-138	10-34	-	-	-	0.03-0.099	
2001	Andersen et al.		76	10	0	Parallel	-	0.057	[60]
						Perpendicular	-	0.052	
1998	Christian et al.	-	62	-		Parallel	Hot box	0.082	[75]
		-	81			Perpendicular		0.057	
1993	McCabe et al.	Wheat	133	20	MC 8.4%	Parallel	-	0.061	[76]
		-	-	-	-	Perpendicular	-	0.048	

## 4.2. Moisture properties

The equilibrium moisture content in straw bales is dependent on the surrounding environment, i.e., relative humidity and temperature [56]. Several studies developed equations to predict the equilibrium moisture content by measuring the relative humidity and temperature within straw bales. Hedlin et al [77] described the correlation between the moisture content within straw and ambient relative humidity at 21.1 °C for five different types of straw. Perry and Green [78] concluded that the sorption isotherm was independent of temperature in the range of 15-50 °C. Lawrence et al. [79] developed an empirical model to predict the moisture content ignoring the temperature effect as the temperature in UK (where the study carried out) was within the range of 15-50 °C. This model, however, is inapplicable to countries with different climate conditions, such as Canada and northern China.

The different types of straw was reported to have negligible impact on the sorption isotherms of straw bales according to the work of [45, 80], while the straw bale from barley was reported to exhibit higher adsorption rate than that from wheat by Ashour et.al [74], which was explained by the porous structure differences observed between barley straw and wheat straw. Yin et.al [45] found that the cut straw with open end reached the equilibrate state more rapidly with the environment by 25% compared to the folded straw with close end. This phenomenon was explained by the larger aspect ratio of the open-ended straw, resulting in more accessed pores for entering moisture content compared with that of closed ended straw. Thus, it was indicated that straw bales trimmed to size can equilibrate more rapidly than straw bales consisting of straws folded at the edge of the bale [32]. A hysteresis pattern between sorption isotherms of straw bales was observed in the work of [80, 81]. Rice straw had a smaller hysteresis than wheat straw and oat straw according to the work of [61, 80]. This indicated that rice straw bales appeared to rapidly recover after wetting, contributing to its hygrothermal performance and durability.

Water vapor resistance factor of straw bales was found highly correlated to their density and a lower density resulted in a lower water vapor resistance factor due to more open spaces between straw fibers [61, 82]. Marques et. al [61] characterized the water resistance factor of



rice straw bales at two densities (i.e., 80 and 100 kg/m<sup>3</sup>) by dry cup and found that the higher density led to an increase of the water vapor resistance factor by 52% (from 3.25 to 5.47). Lebed and Augaitis [82] determined a polynomial function to describe the correlation between the water vapor resistance factor and density (ranging from 60 to 180 kg/m<sup>3</sup>) by using wet cup method:

$$\mu = 2.335 - 0.0127\rho + 0.0000892\rho^2$$

The water absorption of straw bales is highly correlated to their porosity and hygroscopicity. Marques et.al [61] measured the water absorption of rice straw bales at two different densities, i.e., 80 kg/m<sup>3</sup> and 100 kg/m<sup>3</sup> following the standard EN 1609. An increase mass of close to 100% was found at the higher density due to more straw available to absorb water and less space to drain water after immersion. Lebed and Augaitis [82] reported that 60-80% by weight of straw was absorbed during the first 10 hours and then slightly increased, which may be related to the elimination of remaining air from the structure of straw.

#### 4.3. Mechanical properties

Compressive properties plays a major role in mechanical performance of straw bales. Numerous studies have found that the compressive strain-stress curve of straw bales was nonlinear and anisotropic [74, 83, 84]. Also, the deformation of straw bales can be recovered after removing loads. Ashour et al. [74] reported that approximately 10 min to 13 min were required for a complete recovery.

Different types of straw, i.e., such as wheat, oat and barley in Thompson et al. [85] and wheat, rice, corn and sorghum in Maraldi et al. [84] have been reported having limited influence on the mechanical behavior of straw bales. The mechanical properties were mainly influenced by the bale orientation and bale density. Mehravar et al. [69] studied the compressive strength of wheat straw bales at density of 61 kg/m<sup>3</sup> by applying a load parallel and perpendicular to the fibers' orientation, respectively. The compressive strength refers to the maximum stress at 10% deformation. The values obtained for the bales with load direction of parallel and perpendicular were 1.86 kPa and 4.01 kPa, respectively. Platt et al. [48] evaluated the impact of fiber orientation on the compressive behavior of prototype straw bales.

The bales had small dimensions (i.e., 400 mm long, 150 mm width and 150 mm high) with the density of 120 kg/m<sup>3</sup>. Fig. 5 presented the stress-strain curve for the bales oriented parallel and perpendicular. As it can be seen, the straw bales were stiffer by loading perpendicular to the compaction direction. But it should be noted that the response of parallel bales was non-linear and their stiffness was increased with deformation. However, the behavior of perpendicular bales was quasi-linear. This can be attributed to the fact that the non-linear stage was not detected under low loading.

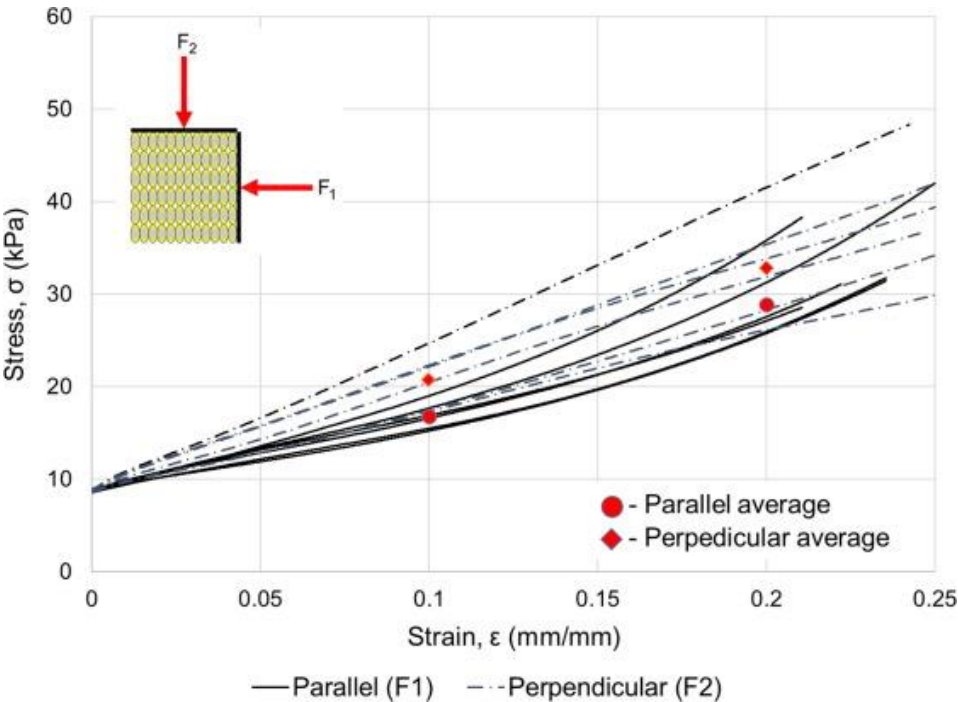


Fig. 5. Stress-strain curve for wheat straw bales oriented parallel and perpendicular [48]

Lecompte et. al [83] studied the mechanical performance of two different batches of wheat straw bales by using two different balers. A compression at a controlled displacement rate of 1 mm/s was directly loaded on straw bales laid flat (loading perpendicular to straw direction) and on-edge (loading parallel to straw direction), respectively. Fig. 6 presented the stress at 10% strain and Young’s modulus of straw bales as a function of density. It was found that the stress and Young’s modulus were dependent of bale orientation for densities in the range of 90-110 kg/m<sup>3</sup>, while the flat bales had higher values than the on-edge bales for densities in the range of 60-70 kg/m<sup>3</sup>. Maraldi et al. [84] investigated the influence of

different parameters (including the types of straw, bale density, bale orientation, baling process and loading rate) on the mechanical performance of straw bales. In their study, the straw bales laid flat and on-edge were produced from eight types of straw (wheat, rice, oat, corn, sorghum and millet) and four levels of strings pre-tension. The obtained densities of the straw bales varied from 66 to 161 kg/m<sup>3</sup>. Three different loading rate (5, 10 and 50 mm/min) were applied to the bales until 60% deformation or failure occurred. The obtained results showed that the stress-strain curve was non-linear for both bale orientations and the flat bales was stiffer than the on-edge bales as mentions before. It was also found that the Young's modulus was dependent on the square of bale density and independent on the strings pre-tension and loading rate. Young's modulus was also found to be dependent on the ratio between straw bulk density and bale density [83].

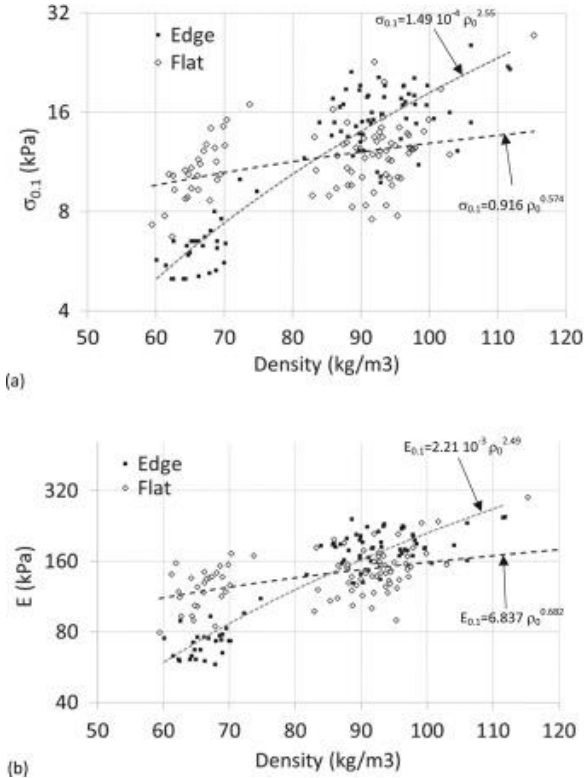


Fig. 6 (a) Stress at 10% strain and (b) Young's modulus versus the initial density of the wheat straw bales

### 4.3. Durability

The mainstream adoption of straw bales as building insulations remains restricted in consideration of the long-term durability. Due to the chemical composition of straw including cellulose, hemicellulose and lignin, straw decomposition can be occurred when ambient hygrothermal condition supports micro-organisms, thus leading to performance degradation and even security issues of buildings. The optimum range of temperature for mold growth is 20-70 °C, and many micro-organisms are restricted at temperatures below 10 °C [79]. According to the studies of [86, 87], no mold growth was observed in wheat straw samples when they were subjected to climate conditions below 80% RH at 10 °C and 70% RH at 25 °C for a 100-day period. Various studies reported that the moisture content within straw bales exceeding the thresholds values ranging from 14% to 27% can cause straw degradation [88, 89]. Generally, the initial moisture content within straw bales at construction not exceeding 14-15% and the moisture content at operation not exceeding 25% are recommended [30]. Robinson et.al [90] found that when the ambient temperature was below 10 °C, straw degradation were not occurred despite of the moisture content within straw bales exceeding to 25% for a prolonged period. Above guidelines give a clear limit on moisture content affecting the durability of straw bales, however, the consequences of exposure duration and subsequent degradation severity are not fully understood.

Thomson and Walker [30] studied and evaluated whether the repeated mold growth was limited for wheat straw bales after an initial mold colonization by conducting two experiments. The first experiment compared the mold growth between fresh wheat straw samples and a wheat straw sample from a three-year-old wall by exposing them to a favorable condition for mold growth at 87% RH and 21.5 °C for 20 days. The old straw sample was found to have not mold growth, while a rapid mold growth was found for the fresh straw samples. The second experiment cyclically exposing the six fresh wheat straw to different elevated levels of relative humidity (from 78% to 91%), including a 28-day period of high relative humidity, 7-day period of drying and 14-day period of re-exposing to the same high relative humidity. The mold growth was not detected a second time for all the samples following drying and re-exposure. Above results revealed that successive mold growth is not

likely to occur if only transient increases in humidity are detected in straw bales.

#### 4.4. Fire resistance

Due to the flammability of loose straw, fire safety is a common concern for straw bale construction. The risk of fire can be reduced through safe fire practice. Additionally, compared to the loose straw, compacted straw bales seems to be more resistant to temperature increase and flame spread because the compression process can remove most oxygen and combustible agent [91].

According to the work of [71], a commercial straw bale was classified to class E following the standard EN 13051-1 [92], representing it is a combustible material and only capable of resisting ignition for a short period. Plastering straw bales, either externally or internally, contributes to the improvement of fire resistance for straw bale walls. A previous study [93] found that the straw bale with a 4 cm plaster layer on both external and internal side survived without severe cracking of the plaster layers or ignition of the straw within the bale when it was exposed to a heat flux of  $29 \text{ kW/m}^2$  for 10 min. In contrast, the un-plastered straw bale was ignited when exposed to the same heat flux. This can be attributed to an insulating barrier between straw bale and heat source and an oxygen transfer barrier between straw bale and air. Wall et.al [94] conducted a fire resistance test on a lime plastered straw bale wall following the standard EN 1364-1 [95]. The lime plaster was found to fall from the straw bale after about 90 min and the exposed straw bale had charred black after further 45 min. The 135 min of fire rating for the plastered straw bale was shown to be exceeding four times the duration compared to the required 30 min according to their local (UK) regulation.

## 5. Properties of straw composites

### 5.1. Thermal insulation properties

The thermal conductivity of different agricultural waste, i.e., wheat straw and barley straw, mixed with soil and sand were studied in the work of [96]. Among composite materials containing 25 wt%, 50 wt% and 75 wt% of straw fiber content, the composites with 75 wt% fiber content exhibited the lowest thermal conductivity,  $0.195 \text{ W/(m}\cdot\text{K)}$  for wheat straw and

0.154 W/(m·K) for barley straw, respectively. This can be attributed to a higher porosity of the composite material with a higher fiber content, leading to the decrease of its thermal conductivity as air has a lower thermal conductivity than solid material [97]. Binici et.al [98] examined the influence of both fiber content and compaction pressure on the thermal conductivity of corn straw-epoxy composites. Two different fiber content, i.e., 57 wt% and 66 wt%, and five compression pressures, i.e., 0.07, 0.12, 0.17, 0.27 kgf/m<sup>3</sup>, were used in sample forming. The lowest thermal conductivity 0.075 W/(m·K) was obtained with 66 wt% of fiber content and 0.07 kgf/m<sup>3</sup> of compaction pressure.

Labat et.al [99] studied the thermal conductivity of straw-clay composites at different densities, which were controlled by adding different percentage of straw fiber content. Their study found that the thermal conductivity values linearly increased from 0.071 to 0.12 W/(m·K) against density values ranging from 241 to 531 kg/m<sup>3</sup>. However, a polynomial rather than linear function between density and thermal conductivity was found for rape straw-clay composites with density ranging from 235 to 714 kg/m<sup>3</sup> according to the work of [100].

Belayachi et. al [49] found that the straw-gypsum composites with density values ranging from 255 to 456 kg/m<sup>3</sup> achieved low thermal conductivity from 0.064 and 0.086 W/(m·K) with acceptable self-bearing ability following the standard NF EN 1992-1-1. Ismail et.al [101] have developed the composite materials from straw fiber, lime and gypsum plaster with three natural additives (hemoglobin, casein and gelatin) to reduce their thermal conductivity and guarantee their self-bearing ability. The thermal conductivity values were found to be decreased after integrating all the additives except for the combination of 5 wt% hemoglobin and 5wt% casein resulting a denser composite than that of without additive. But it should be noted that use of hemoglobin significantly decreased the mechanical properties in the same time due to the porous structure created. In contrast, the mechanical strength was improved when gelatin was added to partially substitute the plaster because gelatin causes a change in the plaster microstructure with the irregular shape and small size of crystals compared to the original large rod-like crystals from the SEM image analysis. The lowest thermal conductivity is 0.057 W/(m·K) when the self-bearing mechanical properties was

ensured.

Many studies attempt to use natural binders, such as starch, alginate and casein, to obtain light and completely biodegradable insulation materials for buildings. Palumbo et.al [102, 103] prepared insulation panels from different agricultural wastes, i.e., barley straw, corn pith and rice husk, mixed with starch or alginate solution. The thermal conductivity of the insulation panels was obtained from 0.052 to 0.098 W/(m·K) for the density values ranging from 89 to 223 kg/m<sup>3</sup>. Tůmová et.al [104] used casein as the binder and obtained straw composites with low thermal conductivity values between 0.045 and 0.056 W/(m·K) for the density values from 72 to 92 kg/m<sup>3</sup>. Also, it was found that the cut straw with smaller fiber length could decrease thermal conductivity compared with the uncut straw. Wei et.al [54] analyzed the influence of fiber size on thermal conductivity of rice straw fiber based insulation boards. In their study, five different size distributions of fiber were obtained by sieving, and the thermal conductivity values of the boards was found to be decreased with the increase of mass fraction of large fibers. Rojas et al. [105] found that the fiber length exerted the greatest impact in determining the thermal conductivity of wheat straw or corn husks based insulation materials compared to the other three parameters including boiling time, NaOH concentration and blending time.

## 5.2. Moisture properties

Fig. 7 shows the measured hygroscopic adsorption isotherm of straw composites from different studies [97, 106, 107]. No significant correlation between adsorption isotherm and density was found, while a higher moisture adsorption rate was observed for a higher porosity based on these studies. Rahim et.al [107] compared the sorption isotherms between hemp lime concrete and rape straw lime concrete with similar density and porosity. The adsorption rate of rape straw lime concrete was higher after the relative humidity reached 75%, and this may be due to the a finer and more homogenous porosity observed in rape straw lime concrete which accelerate the adsorption rate. However, different types of straw in the reinforced concrete has been proposed of having negligible impact on their equilibrium moisture content according to the work of [108].

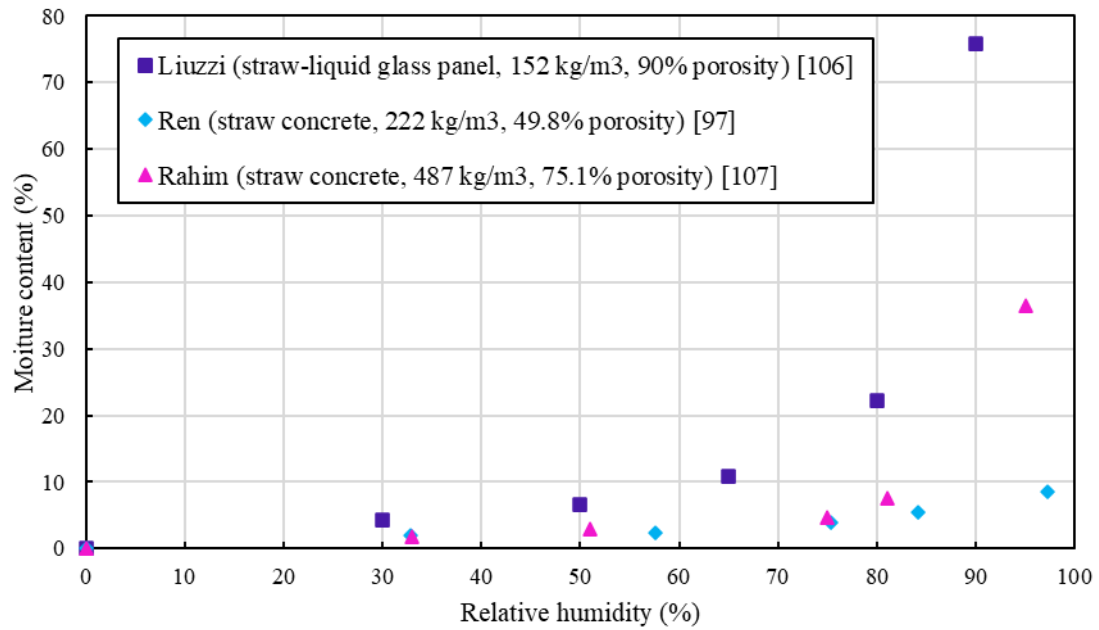


Fig. 7. Equilibrate moisture content based on studies from Liuzzi [106], Ren [97] and Rahim [107]

Fig. 8 summarized the water vapor resistance factor measurements by both the dry cup (denoted by solid point) and wet cup (denoted by hollow point) of straw composites against density from different studies [99, 106, 107, 109-111]. The water resistance factor by wet cup was systematically lower than that determined by dry cup, and this is attributed to the fact that additional liquid transfer driving by capillary forces occurs at high ambient relative humidity. Also, the water vapor resistance factor was shown to be correlated with density based on these studies, except for the lavender straw composite. The observed low water vapor resistance factor for lavender straw composite can be attributed to the presence of highly hydrophilic components in the lavender plant, such as phenolic compounds, flavonoids, anthocyanins or tannins.



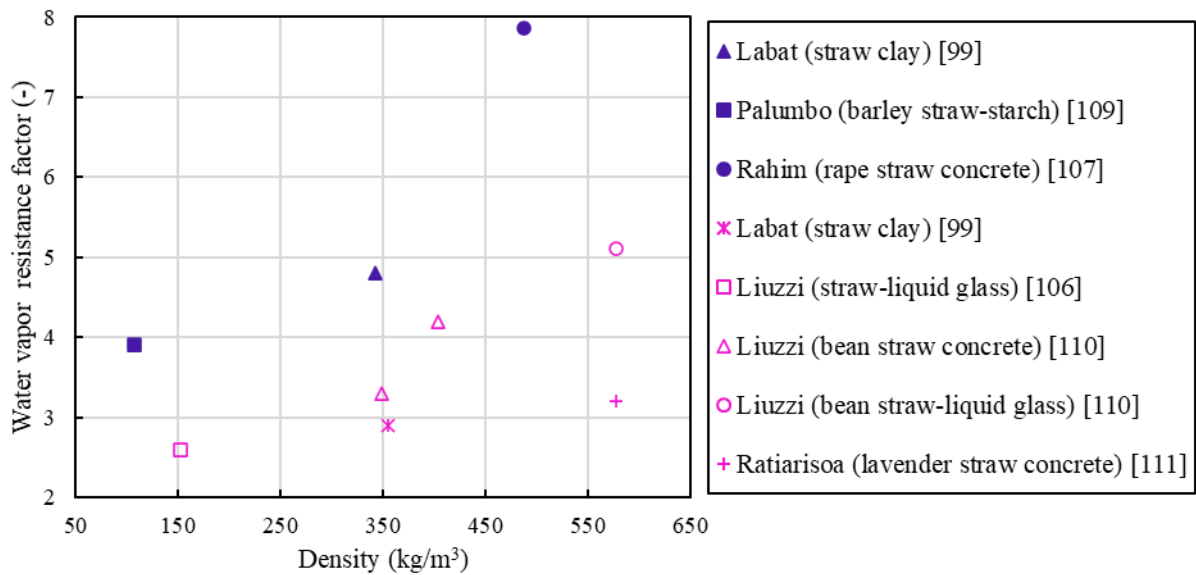


Fig. 8. Water vapor resistance factor (purple and pink represent wet cup and dry cup respectively) versus density based on studies from Labat [99], Liuzzi [106], Rahim [107], Palumbo [109], Liuzzi [110], Ratiarisoa [111]

The moisture buffering value (MBV) of straw composites obtained was found from 2.59 to 3.85 for the density values between 108 kg/m<sup>3</sup> and 577 kg/m<sup>3</sup> from various studies [107, 109, 111, 112]. Therefore, straw composites can be classified as “excellent” following the grading established by Rode et.al [113]. Ahmad et.al [112] studied the moisture buffering capacity of corn straw reinforced concrete. Three different weight percentages of corn straw to binder, i.e., 33 wt%, 55 wt% and 100 wt% were used, and the results revealed that the MBV increased with an increasing straw content. Rahim et.al [107] measured the MBV of rape straw concrete samples in different thickness according to the NORDTEST protocol [114], and it was found that the MBV increased by 13.1% (from 2.29 to 2.59) when the thickness increased from 3 cm to 7 cm.

Few studies have studied the water absorption of straw composite materials. In one of them, corn straw reinforced concrete samples were immersed in water for 15 days, and it was found that the samples with the averaged 14 mm fiber size had a larger amount of water absorbed in than that of samples with 9 mm fiber size at any given fiber content (between 5 wt% and 30% wt) [115]. Also, the water absorption rate was found the maximum during the first 60 minutes and decreased gradually for all the formulations. The highest total water

absorption rate of 77.9%, was obtained for the formulation with a fiber content of 30 wt% and a size of 14 mm. This can be attributed to the hydrophilic nature of the corn straw fiber and the higher porous structure created by the larger fiber size. Zuo et.al [116] examined the influence of silicone-acrylic emulsion addition on water absorption of rice straw magnesium cement composites by immersing the composite samples in water for 24 hours according to GB/T 24312. A decrease of water absorption by 32% was observed as the silicon-acrylic emulsion increased by 10%.

### 5.3. Mechanical properties

The mechanical performance of straw composites is of great importance according to international and European standards for thermal insulation applications. A higher mechanical performance can be obtained with a higher density due to the less voids in the composites [54, 117]. Straw composites compacted by machines had a higher compressive strength compared with the manual compaction [112]. Ahmad et al. [112] examined the effect of binder content on the mechanical performance of corn straw composites. The results indicated that the compressive strength and the flexural strength were enhanced with an increase in the amount of cement and gypsum, respectively. A study carried out by Ismail et. al [101] found that the addition of 5% of hemoglobin to the lime induced a drastic decrease in the mechanical strength of the composites based on straw and mineral binders. However, the addition of 5% hemoglobin and 5% casein improved the mechanical properties by three times compared with pure lime.

Bakatovich et.al [51] studied the compressive strength and flexural strength of straw composites from different types of straw (rye, barley, wheat, oats, and rice). It was found that for equal density and thermal conductivity, the composite from rye straw exhibited higher mechanical properties by increasing 21-52% of compressive strength and 26-54% of flexural strength compared with the composites from barley, wheat, oats and rice straw. This can be attributed to the large strength provided by the thick outer parts of stems of rye straw. Bakatovich et.al [118] have found that replacing a half of moss by rye straw enhanced the mechanical properties of the liquid glass bonded composites. In particular, the compressive strength at 10% deformation and the flexural strength increased from 0.18 MPa to 0.30 MPa and from 0.08 MPa to 0.26 MPa, respectively. Pachla et al. [119] examined the influence of adding rice straw and rice husk on the mechanical properties of cellulose concrete composites. It was found that the addition of rice straw reduced their compressive strength but increased their flexural strength.

Wei et.al [54] analyzed the influence of fiber size on the internal bonding strength (IB) and the modulus of rupture (MOR) of rice straw fiber based insulation boards. The obtained

results indicated that the IB and MOR increased initially followed by a reduction with the increase of fiber size. This can be attributed to the less binder required for the larger fiber size with less surface area, which could decrease the binder distribution of unit area of the straw fibers, and thus enhanced the mechanical properties of the boards. However, increasing the fine fibers could also decrease the proportion of rice straw surface that contains high amount of wax and inorganic silicon, leading to an intimate contact between fibers, and consequently improved the mechanical properties.

Different straw treatment methods can be used to improve mechanical properties of straw composites. Wang et.al [120] have studied the influence of NaOH treatment with different mass fraction (from 0 wt% to 8wt%) on the mechanical properties of rice straw concrete. The results indicated that the chemically treated straw fiber enhanced mechanical properties when the mass fraction of NaOH was lower than 3%. Also, for the treatment time of 150 min, the compressive strength and flexural strength reached the maximum value of 12.45 MPa and 4.83 MPa. Dušek et al. [121] evaluated the effect of water and NaOH treatment on the flexural strength of rape straw bonded by bone glue with sodium lignosulfonate. It was found that both the treatment methods enhanced the flexural strength of the composites. In particular, the composites subjected to the water treatment exhibited higher strength compared with the NaOH treatment. Table 5 shows the thermal, moisture, mechanical properties of straw composites.

Table 5 Thermal, moisture and mechanical properties of straw composites as found in literature published by various authors

Straw type	Fiber length (mm)	Binder type	Fiber/binder mass ratio	Density (kg/m <sup>3</sup> )	Porosity	Thermal conductivity (kg/m·K)	Vapor resistance factor		MBV (g/m <sup>2</sup> %RH)	Compression strength (MPa)	Bending strength (MPa)	Ref
							Dry	Wet				
Rye, barley, wheat, oats, rice	20-40, <80	Liquid glass	1/1.4	200-220	-	0.056-0.063	-	-	-	0.23-0.35	0.50-0.82	[51]
Rice	10-30	Methylene diphenyl diisocyanate (MDI) resin	1/0.08	200-350	-	0.051-0.053	-	-	-	-	0.16-2.6	[54]
Corn	0.5-4	Epoxy	60/30, 60/45	260-410	-	0.075-0.159	-	-	-	0.11-0.29	0.04-0.13	[98]
Rape	-	Clay	-	241-531	-	0.071-0.12	4.8	2.9	-	-	-	[99]
Rape	-	Clay	1/2.4	438	-	0.07	-	-	-	-	-	[100]
Wheat	<50	Tradical PF70, Tradical Thermo, plaster	0.2-0.4	-	-	0.054-0.069	-	-	-	0.009-0.18	-	[101]
Rye	-	Casein	1/0.6, 1/0.5, 1/0.4, 1/0.3	72-93	-	0.045-0.056	-	-	-	-	0-1	[104]
Barley	-	Sodium silicate solution	70/30	152	0.9	0.058	-	2.59	-	-	-	[106]
Rape	-	Lime	14/36	487	0.75	-	7.87	-	2.9	-	-	[107]
Barley	-	Starch	81/19	108	0.92	0.042	3.9	3.4	3.2	-	-	[109]
Bean	-	Clay and cement, liquid glass	0.49	348-580	-	0.075-0.096	-	3.3-5.1	-	-	-	[110]
Lavender	-	Pozzolanic	0.46, 1.51	557,	-	0.142, 0.146	-	3.2, 2	3.85, 3.5	0.70-0.22	-	[111]

Rape	0-120	Bone glue with sodium lignosulfonate	1/0.35	661 500-700	-	-	33-36	23-26	-	-	2.9-3.4	[121]
Flax	-	Liquid glass	1/2.4, 1/2	312, 336	-	0.084, 0.085	-	-	-	-	-	[122]

---

### 5.3. Durability

Belayachi et.al [49] studied the changes of thermal insulation and mechanical performance as well as the degradation of both wheat straw-plaster and barley straw-plaster composites when they are exposed to dry-wet and freeze-thaw cycling. The composites were cyclically immersed for 1 hour in water prior to natural drying for 71 hours during dry-wet tests, and they were exposed to a cycle between -10 °C and 40 °C during the freeze-thaw tests. The results demonstrated that both the composites were more sensitive to the dry-wet aging than the freeze-thaw aging. Also, although the barley-based material showed the lower thermal conductivity and better mechanical properties in non-aged state, the barley-based material was more likely to lose its performances under the aging conditions due to its more porous structure resulting in higher moisture absorption rate compared with the wheat-based material. Significant mass loss was observed at the 35th cycle for the barley straw composite, while the wheat straw composite remained relatively complete at the 40th cycle, as shown in Fig. 9.

There is high possibility of mold growth in straw-based materials when they are subjected to excessive moisture environment. In the work of [123], mold growth was found on barley straw after two weeks exposing to 93% RH, whereas no mold growth was observed when exposing to 84% RH. A study carried out by Giroudon et.al [124] found that the mold growth of straw composites was dependent on the different types of straw, i.e., barley straw and lavender straw. In their study, the earth composites containing 3% of barley straw or lavender straw were exposed to a favorable environment for mold growth, i.e., 93% RH and 30 °C. The lavender reinforced composite was found to be more resistant to mold growth than barley reinforced composite, and this result was explained by the special chemical composition of lavender containing polyphenols and aroma with antibacterial, antifungal and insecticidal qualities. A comprehensive study that have been done by Viel et.al [125] revealed that the pH of a given material is a significant indicator of mold growth as the use of alkali treated rape straw to prepare composites does not show decay after exposing them to a unfavorable condition, i.e., 90% RH and 30 °C for three months. Also, the water absorption of

material was found to be an influencing factor as the addition of paraffin decreased water content within composite, leading to lower kinetics of mold growth on its exposed surface.



Fig. 9. State of barley and wheat straw composites after 35 and 40 drying-wetting cycles respectively

#### 5.4. Fire resistance

The fire reaction of straw composites is a crucial aspect that should be well-known and improved due to the high flammability of straw fibers. A study carried out by Babenko et. al [122] found that a liquid glass bonded flax straw composite had slower thermal decomposition and shorter peaks in comparison to a pure flax straw. This result can be caused by mineralization of the flax straw when treated with liquid glass. A comprehensive study that has been done by Palumbo et.al [103] revealed that binders, even in small proportions, has a significant influence on fire resistance of bio-based insulation composites made by three crop by-products, i.e., barley straw, corn pith and rice husk, and two binders, i.e., starch and alginate. The barley straw composite using approximately 6% alginate as binder showed superior fire resistance than that of using about 9% starch as binder based on flammability (including PCFC, LOI, ignition time and extinguish ability) and thermal degradation tests. Also, the different types of crop by-product had negligible effect on the fire behavior of resulting composites. This is confirmed by another study that thermal degradation of straw composites was mostly affected by the binder nature, i.e., lime and plaster, compared with the fiber variety, i.e., wheat straw and barley straw [126].



## 6. Life cycle assessment

Life cycle assessment (LCA) is commonly used to assess the environmental footprint of a insulation product. Generally, the LCA is performed using cradle-to-grave approach (where the evaluation performed from the material extraction to the disposal) or cradle-to-gate (where the evaluation does not include the use and the disposal phases) approaches [127]. D'Alessandro et al. [128] compared the cradle-to-grave assessment of a straw bale and other insulation materials (see Table 6) based on two impact categories. In this case the functional unit is 1 kg of materials. The straw bale was shown to have low values of primary energy and global warming potential compared with the traditional mineral insulation materials. González et al. [129] studied the energy and carbon footprints of straw bales and straw-clay blocks for local conditions by comparison with traditional fired bricks and concrete blocks in Andean Patagonia. It was found that the carbon emission and embodied energy of straw bales and straw-clay blocks to cover 1 m<sup>2</sup> of wall was smaller compared to the fired bricks and concrete block, as shown in Table 7. Considering that different materials could vary in density and thermal conductivity values, a more appropriate unit such as the mass of materials to provide a equal thermal resistance, could be used for a fair comparison. Borjes et al. [130] conducted the LCA on the entire manufacturing process of clay bricks with and without the incorporation of biobased additives, i.e., 1 wt% wheat straw, 2 wt% olive stone flour, 2 wt% glycerol carbonate and 2 wt% dimethyl carbonate. The functional unit was 1 m<sup>2</sup> clay tablets with an equivalent thermal resistance of 0.035 m<sup>2</sup>W/K. It was found that the additives reduced the environmental impact compared to the pure clay brick.

Table 6 Comparative life cycle analysis of straw bale with other insulation materials [128]

Insulation	Primary energy inputs (MJ-eq/kg)	GHG (kgCO <sub>2</sub> -eq/kg)	impact	Processes included
Straw bale	0.89	0.18 <sup>b</sup>		E+M+T
Expanded polystyrene	114	107		E+M+D+T
Extruded polystyrene	107	13.67		E+M+D+T
Mineral wool	44	2.31		E+M+T
Kenaf	39	2.09		E+M+T

Hemp	n.a. <sup>c</sup>	0.15 <sup>b</sup>	E+M+T
------	-------------------	-------------------	-------

<sup>a</sup> E = raw materials extraction; M = manufacturing; T= transports; D = disposal.

<sup>b</sup> Without carbon sequestration.

<sup>c</sup> n.a. = not available.

Table 7 Embodied energy and global warming potential of straw bales, fired bricks and concrete blocks for

1 m<sup>2</sup> of wall [129]

Number required per m <sup>2</sup> of wall	Thermal conductivity (W/m·K)	Thermal transmittance (W/m·K)	Embodied energy (MJ/m <sup>2</sup> )	Global warming potential (kgCO <sub>2</sub> -eq/m <sup>2</sup> )
85 Fired bricks	0.90	3.9	488 <sup>a</sup>	30
11 concrete blocks	0.64	3.2	169 <sup>b</sup>	9.6
7 straw-clay blocks	0.18	0.86	40	3.4
3 straw bales	0.07	0.16	28	2.5
3 half straw bales	0.07	0.32	14	1.3

<sup>a</sup> Includes 700 km transport.

<sup>b</sup> Includes 700 km transport in 10% of weight due to cement

Quintana-Gallardo et al. [131] compared the cradle-to-gate assessment of a rice straw wall and a traditional double brick wall. The straw wall was more insulating with thermal resistance doubled that of the traditional wall. It was found that the environmental impact of the straw wall was lower in every category except for the land use and water use compared to the traditional double brick wall. Moreover, by substituting the two different waste management, i.e., burning straw or mix straw with soil, 1 m<sup>2</sup> rice straw wall can prevent the emission of 18.85 kgCO<sub>2</sub>-eq and 52.64 kgCO<sub>2</sub>-eq, respectively. Cornaro et al. [70] conducted the LCA of an innovative wall (which was composed of straw bale and natural plasters) and a traditional clay brick wall. In this case the straw wall and the traditional wall had the same thermal resistance of 6.5 m<sup>2</sup>W/K and the functional unit was the area of the wall package installed in a reference building. The obtained results demonstrated that the CO<sub>2</sub> equivalent emission and the embodied energy of the straw wall was 50% lower than the traditional wall regarding the phases of production and construction. Cascone et al. [132] compared the embodied energy of a platform system made of pressed straw and a cross laminated timber (XLAM) system with the same thermal performance. The platform system led to a reduction of embodied energy of 60% compared with the XLAM system.

A dynamic LCA and a static LCA were done by Zieger et al. [133], who compared the cradle-to-gate assessment of a wheat straw wall and a traditional concrete wall with an insulation layer of mineral wool. Both the walls had the same thermal resistance value of 7.3 m<sup>2</sup>W/K and the functional unit was 1 m<sup>2</sup> of wall. It was found that the traditional wall had minor changes in equivalent carbon emission regardless of the LCA method, while the straw wall had larger difference by using different LCA method. Specifically, the equivalent carbon emission calculated by dynamic LCA was lower than the static LCA calculated at 100 years and the dynamic equivalent carbon emission converged toward the static one after a long-time horizon, as shown in Table 8. This is because the traditional wall contributes to the climate change from the first year, whereas the straw wall has a cooling effect for several years, which are ignored when using the static method.

Table 8 Relative global warming potential of straw wall and concrete wall calculated by static and dynamic life cycle analysis [133]

Insulation	Conventional (kgCO <sub>2</sub> -eq/FU)	Straw-based (kgCO <sub>2</sub> -eq/FU)
Static GWP100	79.8	26.3
	GHG	GHG (min/max)
Dynamic DLCA 20	60.0	-56.5
Dynamic DLCA 100	70.8	-22.2/-9.8
Dynamic DLCA 500	71.8	9.8/14.3
Dynamic DLCA 1000	71.2	11.1/13.7

\*Straw's end of life is regarded as 50% composted and 50% incinerated

## 7. Conclusions

The appropriate utilization of straw waste in building insulation materials is a promising approach for energy efficiency and decarbonization. In this paper, straw insulation is categorized as straw bale and straw composite. Straw bales are produced by using bale machines to collect and compress the deposited straw after harvesting crops. Straw composites are prepared by molding straw fibers with alternative binders. This paper presents the available researches on the thermal insulation, moisture, mechanical properties, durability and fire resistance of straw insulation with the consideration of different factors. Also, the

environmental impact of straw wall is also proposed by comparison with the traditional wall.

The main findings were drawn as follows:

- Thermal conductivity is the most significant property that characterizes the effectiveness of a thermal insulation material. Thermal conductivity values of straw bales are reported to have high variability in the range of 0.03 to 0.08 W/(m·K), which can be caused by various factors, including the types of straw, the bale density, the orientation to heat flow, the ambient temperature and relative humidity. Meanwhile, increasing fiber content and fraction of large fibers within straw composites effectively decreased their thermal conductivity.
- The moisture properties of straw bales and straw composites have been observed to be influenced by various factors. Straw bales with open-ended straw could reach the equilibrium humidity more rapidly with environment than bales with close-ended straw. The water vapor permeability of both straw bales and straw composites have been observed to be dependent on their density. However, the types of straw and the density have no significant impact on the moisture absorption of straw composites. Furthermore, factors such as the fiber content, the hydrophilic nature of the fiber, the fiber size, the porosity and the thickness affect the moisture buffering capacity and water absorption.
- The mechanical performance of straw bales and straw composites plays an essential role. Straw bales exhibit a non-linear stress-strain behavior and bales laid flat is stiffer than bales laid on-edge. A higher mechanical performance can be obtained with a higher density due to the less voids in the composites. Moreover, the types of straw, treatment methods and fiber size affect the mechanical performance of straw composites.
- The durability and fire resistance of a material are crucial aspects to ensure the long service-life of the building. A favorable hygrothermal conditions for micro-organism results in mold growth, thus leading to straw degradation. The moisture content at operation not exceeding 25% is generally recommended to prevent degradation of straw bales. Plastered straw bales show better fire

resistance than un-plastered straw bales. Binders, even in small proportions, has a significant influence on fire resistance of straw composites. In addition, building insulation materials from straw have low embodied energy and low carbon emission.

In conclusion, straw is a promising raw material to obtain cost-effective and eco-friendly thermal insulation materials for buildings. Nevertheless, compared to the less environment-friendly insulation materials, straw insulation materials present some disadvantage and issues, which should be addressed in the future. Different approaches can be used to improve the durability and fire resistance of straw insulation materials, such as surface treatments, harmless biocidal and retardant addition. Also, the risk of straw degradation should be further investigated with long-term exposure to favorable conditions for mold growth. Additionally, inherent mechanisms of various factors, such as fiber size distribution and pore size distribution are not clear. A microscale analysis could be conducted on these factors correlating to the performance of straw insulation products to provide guidelines for their optimal design. A multi-criteria assessment method for comprehensively rating various technical properties needs to be explored in future to select the desirable options when different scenarios are assumed.

## **Acknowledgement**

The authors would like to thank the Région Auvergne-Rhône-Alpes for its financial contributions. In addition, the authors would like to thank the CSC (China Scholarship Council) to provide financial support for the study in France.

## **References**

- [1] Y. Zhang, C.-Q. He, B.-J. Tang, Y.-M. Wei, China's energy consumption in the building sector: a life cycle approach, *Energy and Buildings* 94 (2015) 240-251.
- [2] Y.X. Ma, C. Yu, Impact of meteorological factors on high-rise office building energy consumption in Hong Kong: From a spatiotemporal perspective, *Energy and Buildings* 228 (2020) 110468.
- [3] A. Sieminski, Annual energy outlook 2015, US Energy Information Administration (2015).
- [4] L. Yang, H. Yan, J.C. Lam, Thermal comfort and building energy consumption implications—a review, *Applied energy* 115 (2014) 164-173.
- [5] B. Abu-Jdayil, A.-H. Mourad, W. Hittini, M. Hassan, S. Hameedi, Traditional, state-of-the-art and renewable

thermal building insulation materials: An overview, *Construction and Building Materials* 214 (2019) 709-735.

- [6] U.Y.A. Tettey, A. Doodoo, L. Gustavsson, Effects of different insulation materials on primary energy and CO<sub>2</sub> emission of a multi-storey residential building, *Energy and buildings* 82 (2014) 369-377.
- [7] S.S. Hassan, G.A. Williams, A.K. Jaiswal, Emerging technologies for the pretreatment of lignocellulosic biomass, *Bioresource technology* 262 (2018) 310-318.
- [8] L. Li, Y. Wang, Q. Zhang, J. Li, X. Yang, J. Jin, Wheat straw burning and its associated impacts on Beijing air quality, *Science in China Series D: Earth Sciences* 51(3) (2008) 403-414.
- [9] J. Zhao, S. Li, Life cycle cost assessment and multi-criteria decision analysis of environment-friendly building insulation materials-A review, *Energy and Buildings* (2021) 111582.
- [10] EN12664, Thermal performance of building materials and products-Determination of thermal resistance by means of guarded hot plate and heat flow meter methods-Dry and moist products of medium and low thermal resistance, British Standard, 2001.
- [11] EN12667, Thermal performance of building materials and products-Determination of thermal resistance by means of guarded hot plate and heat flow meter methods-Products of high and medium thermal resistance, British Standard, 2001.
- [12] EN12939, Thermal performance of building materials and products-Determination of thermal resistance by means of guarded hot plate and heat flow meter methods-Thick products of high and medium thermal resistance, British Standard, 2001.
- [13] A. C518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, ASTM International, West Conshohocken, PA, 2017.
- [14] I. 11357, Plastics-Differential scanning calorimetry (DSC)-Part 1: General principles, International Organization for Standardization, 2016.
- [15] I. 22007, Plastics-Determination of thermal conductivity and thermal diffusivity, International Organization for Standardization, 2017.
- [16] A.D.-. 16, Standard Test Method for Measurement of Thermal Effusivity of Fabrics Using a Modified Transient Plane Source (MTPS) Instrument, ASTM International, 2016.
- [17] E.I. 12571, Hygrothermal performance of building materials and products-Determination of hygroscopic sorption properties, British Standard, 2013.
- [18] E.I. 12086, Thermal insulating products for building applications-Determination of water vapour transmission properties, British Standard, 2013.
- [19] E.I. 12572, Hygrothermal performance of building materials and products-Determination of water vapour transmission properties-Cup method, British Standard, 2016.
- [20] J.A. 1470-1, Determination of water vapour adsorption/desorption properties for building materials-Part 1: Response to humidity variation, Japanese Industrial Standard, 2002.
- [21] C. Rode, R. Peuhkuri, H. Lone, B. Time, A. Gustavsen, T. Ojanen, J. Ahonen, K. Svennberg, L.-E. Harderup, J. Arfvidsson, Moisture buffering of building materials, Technical University of Denmark DTU2006.
- [22] I. 24353, Hygrothermal performance of building materials and products — Determination of moisture adsorption/desorption properties in response to humidity variation, International Organization for Standardization, 2008.
- [23] N. 51-071, Determination of burning behaviour by oxygen index, Association Francaise de Normalisation, 1985.
- [24] I. 29767, Thermal insulating products for building applications-Determination of short-term water

- absorption by partial immersion, International Organization for Standardization, 2019.
- [25] E.I. 12087, Thermal insulating products for building applications-Determination of long term water absorption by immersion, British Standard, 2013.
- [26] E. 826, Thermal insulating products for building applications - Determination of compression behaviour, British Standard, 2013.
- [27] E. 1608, Thermal insulating products for building applications - Determination of tensile strength parallel to faces, British Standard, 2013.
- [28] E. 1607, Thermal insulating products for building applications - Determination of tensile strength perpendicular to faces, British Standard, 2013.
- [29] E. 12089, Thermal insulating products for building applications - Determination of bending behaviour, British Standard, 2013.
- [30] A. Thomson, P. Walker, Durability characteristics of straw bales in building envelopes, *Construction and Building Materials* 68 (2014) 135-141.
- [31] P. Johansson, A. Ekstrand-Tobin, T. Svensson, G. Bok, Laboratory study to determine the critical moisture level for mould growth on building materials, *International Biodeterioration & Biodegradation* 73 (2012) 23-32.
- [32] A. E24-16, Laboratory Method for Evaluating the Mold Resistance of Wood-based Materials: Mold Chamber Test, American Wood Protection Association, 2016.
- [33] A. D3273, Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber, ASTM International, 2012.
- [34] B.E.I. 846, Plastics. Evaluation of the action of microorganisms, British Standards Institute, 1997.
- [35] B.E. 13501-1, Fire classification of construction products and building elements. Classification using data from reaction to fire tests, British Standards Institute, 2018.
- [36] I. 5660-1, Reaction-to-fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement), International Organization for Standardization, 2015.
- [37] A. E1354, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, ASTM International, 2016.
- [38] A. D7309, Standard Test Method for Determining Flammability Characteristics of Plastics and Other Solid Materials Using Microscale Combustion Calorimetry, ASTM International, West Conshohocken, PA, 2007.
- [39] I. 4589, Plastics-Determination of burning behaviour by oxygen index, International Organization for Standardization, 2017.
- [40] S.H. Ghaffar, M. Fan, Structural analysis for lignin characteristics in biomass straw, *Biomass and bioenergy* 57 (2013) 264-279.
- [41] J.O. Titiloye, M.S.A. Bakar, T.E. Odetoeye, Thermochemical characterisation of agricultural wastes from West Africa, *Industrial crops and products* 47 (2013) 199-203.
- [42] S. Ghaffar, Straw fibre-based construction materials, *Advanced High Strength Natural Fibre Composites in Construction*, Elsevier 2017, pp. 257-283.
- [43] A.J. Stamm, Wood and cellulose science, *Wood and cellulose science*. (1964).
- [44] H. Yu, R. Liu, D. Shen, Z. Wu, Y. Huang, Arrangement of cellulose microfibrils in the wheat straw cell wall, *Carbohydrate polymers* 72(1) (2008) 122-127.
- [45] X. Yin, M. Lawrence, D. Maskell, M. Ansell, Comparative micro-structure and sorption isotherms of rice straw and wheat straw, *Energy and Buildings* 173 (2018) 11-18.
- [46] S. R.-C, J. Tomkinson, Appendix 1. Essential Guides for Isolation/Purification of polysaccharides, (2000).

- [47] R. Sun, Cereal straw as a resource for sustainable biomaterials and biofuels: chemistry, extractives, lignins, hemicelluloses and cellulose, Elsevier 2010.
- [48] S. Platt, D. Maskell, P. Walker, A. Laborel-Préneron, Manufacture and characterisation of prototype straw bale insulation products, *Construction and Building Materials* 262 (2020) 120035.
- [49] N. Belayachi, D. Hoxha, M. Slaimia, Impact of accelerated climatic aging on the behavior of gypsum plaster-straw material for building thermal insulation, *Construction and Building Materials* 125 (2016) 912-918.
- [50] M. Ali, A. Alabdulkarem, A. Nuhait, K. Al-Salem, G. Iannace, R. Almuzaier, A. Al-turki, F. Al-Ajlan, Y. Al-Mosabi, A. Al-Sulaimi, Thermal and acoustic characteristics of novel thermal insulating materials made of Eucalyptus Globulus leaves and wheat straw fibers, *Journal of Building Engineering* 32 (2020) 101452.
- [51] A. Bakatovich, N. Davydenko, F. Gaspar, Thermal insulating plates produced on the basis of vegetable agricultural waste, *Energy and Buildings* 180 (2018) 72-82.
- [52] C. Lacoste, R. El Hage, A. Bergeret, S. Corn, P. Lacroix, Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation, *Carbohydrate polymers* 184 (2018) 1-8.
- [53] P. Evon, V. Vandebossche, P.-Y. Pontalier, L. Rigal, New thermal insulation fiberboards from cake generated during biorefinery of sunflower whole plant in a twin-screw extruder, *Industrial Crops and Products* 52 (2014) 354-362.
- [54] K. Wei, C. Lv, M. Chen, X. Zhou, Z. Dai, D. Shen, Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing, *Energy and Buildings* 87 (2015) 116-122.
- [55] X.-y. Zhou, F. Zheng, H.-g. Li, C.-l. Lu, An environment-friendly thermal insulation material from cotton stalk fibers, *Energy and Buildings* 42(7) (2010) 1070-1074.
- [56] T. Ashour, The use of renewable agricultural by-products as building materials, *Work* 2 (2003) 013-2467034.
- [57] J.-P. Costes, A. Evrard, B. Biot, G. Keutgen, A. Daras, S. Dubois, F. Lebeau, L. Courard, Thermal Conductivity of Straw Bales: Full Size Measurements Considering the Direction of the Heat Flow, *Buildings* 7(4) (2017) 11.
- [58] A. Shea, K. Wall, P. Walker, Evaluation of the thermal performance of an innovative prefabricated natural plant fibre building system, *Building Services Engineering Research and Technology* 34(4) (2012) 369-380.
- [59] L. Conti, M. Barbari, M. Monti, Steady-state thermal properties of rectangular straw-bales (RSB) for building, *Buildings* 6(4) (2016) 44.
- [60] B.M. Andersen, J. Munch-Andersen, Halmballer og muslinger som isoleringsmaterialer, Sampling and testing report, Danish Building Research Institute (2001).
- [61] B. Marques, A. Tadeu, J. Almeida, J. António, J. de Brito, Characterization of sustainable building walls made from rice straw bales, *Journal of Building Engineering* (2019) 101041.
- [62] M. Reif, J. Zach, J. Hroudová, Studying the properties of particulate insulating materials on natural basis, *Procedia Engineering* 151 (2016) 368-374.
- [63] S. Cascone, G. Evola, A. Gagliano, G. Sciuto, C. Baroetto Parisi, Laboratory and in-situ measurements for thermal and acoustic performance of straw bales, *Sustainability* 11(20) (2019) 5592.
- [64] J. VĚJELIENĚ, A. Gailius, S. VĚJELIS, S. Vaitkus, G. BALČIŪNAS, Evaluation of structure influence on thermal conductivity of thermal insulating materials from renewable resources, *Materials Science* 17(2) (2011) 208-212.
- [65] J. VĚjeliene, Processed Straw as Effective Thermal Insulation for Building Envelope Constructions, *Engineering Structures and Technologies* 4(3) (2012) 96-103.



- [66] O. Douzane, G. Promis, J.-M. Roucoult, A.-D. Tran Le, T. Langlet, Hygrothermal performance of a straw bale building: In situ and laboratory investigations, *Journal of Building Engineering* 8 (2016) 91-98.
- [67] F. Strohhallenbau, Thermal performance: strawbale building research development 2003–2009, Beetendorf, Germany: FASBA (2009).
- [68] K.A. Sabapathy, S. Gedupudi, Straw bale based constructions: Measurement of effective thermal transport properties, *Construction and Building Materials* 198 (2019) 182-194.
- [69] M. Mehravar, A. Veshkini, S. Veisheh, R. Fayaz, Physical Properties of Straw Bale and its Effect on Building Energy Conservation and Carbon Emissions in Different Climatic Regions of Iran, *Energy and Buildings* (2021) 111559.
- [70] C. Cornaro, V. Zanella, P. Robazza, E. Belloni, C. Buratti, An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment, *Energy and Buildings* 208 (2020) 109636.
- [71] D.I.f.B. DIBt, Thermal insulation made of straw bales, (2017).
- [72] M. Volf, J. Diviš, F. Havlík, Thermal, moisture and biological behaviour of natural insulating materials, *Energy Procedia* 78 (2015) 1599-1604.
- [73] S. Goodhew, R. Griffiths, Sustainable earth walls to meet the building regulations, *Energy and Buildings* 37(5) (2005) 451-459.
- [74] T. Ashour, H. Georg, W. Wu, Performance of straw bale wall: A case of study, *Energy and Buildings* 43(8) (2011) 1960-1967.
- [75] J. Christian, O. Desjarlais, P. Stovall, Straw-bale wall hot box test results and analysis, ASRAE Conf., Florida, 1998.
- [76] J. McCabe, The thermal resistivity of straw bales for construction, Unpublished Master's thesis. Department Nuclear Engineering University of Arizona, Tucson, AZ (1993).
- [77] C.P. Hedlin, Sorption isotherms of five types of grain straw at 70 F, National Research Council of Canada, Division of Building Research 1967.
- [78] H. Perry Robert, W. Green Don, O. Maloney James, Perry's chemical engineers' handbook, Mc Graw-Hills New York (1997) 56-64.
- [79] M. Lawrence, A. Heath, P. Walker, Determining moisture levels in straw bale construction, *Construction and Building Materials* 23(8) (2009) 2763-2768.
- [80] J. Carfrae, The moisture performance of straw bale construction in a temperate maritime climate, (2011).
- [81] J. Carfrae, P. De Wilde, J. Littlewood, S. Goodhew, P. Walker, Development of a cost effective probe for the long term monitoring of straw bale buildings, *Building and Environment* 46(1) (2011) 156-164.
- [82] A. Lebed, N. Augaitis, Research of physical properties of straw for building panels, *Int. J. Eng. Sci. Invention* 6(5) (2017) 9-14.
- [83] T. Lecompte, A. Le Duigou, Mechanics of straw bales for building applications, *Journal of Building Engineering* 9 (2017) 84-90.
- [84] M. Maraldi, L. Molari, N. Regazzi, G. Molari, Analysis of the parameters affecting the mechanical behaviour of straw bales under compression, *biosystems engineering* 160 (2017) 179-193.
- [85] K. Thompson, *Straw Bale Construction: A Manual for Maritime Regions*, Ship Harbour, Nova Scotia, Canada: Beautiful Sustainable Buildings (1995).
- [86] W. Hofbauer, K. Breuer, N. Krueger, K. Sedlbauer, Toxic mould versus façade-jungle—a comparison of undesirable biological growth on indoor surfaces and outer building coatings, *Proceedings of the 10th International Conference on Indoor Air Quality and Climate—Indoor Air 2005*, 2005, pp. 2450-2454.
- [87] W. Hofbauer, N. Kreuger, K. Breuer, K. Sedlbauer, T. Schoch, Mould resistance assessment of building

- materials—Material specific isopleth systems for practical application, *Indoor Air* (2008) 17-22.
- [88] M.D. Summers, S.L. Blunk, B.M. Jenkins, How straw decomposes: Implications for straw bale construction, *Ecological Building Network* (2003).
- [89] A.S. Steen, B. Steen, D. Bainbridge, *The straw bale house*, Chelsea Green Publishing 1994.
- [90] J. Robinson, H.K. Aoun, M. Davison, Determining moisture levels in straw bale construction, *Procedia engineering* 171 (2017) 1526-1534.
- [91] B. King, M. Aschheim, *Design of straw bale buildings: the state of the art*, (2006).
- [92] E. 13501-1:2007+A1:2009, Fire classification of construction products and building elements. Classification using test data from reaction to fire tests, *British Standard*, 2007.
- [93] V. Apte, B. Paroz, A. Bhargava, Fire safety testing and modelling of rendered strawbales for construction in bushfire prone areas, (2003).
- [94] K. Wall, P. Walker, C. Gross, C. White, T. Mander, Development and testing of a prototype straw bale house, *Proceedings of the Institution of Civil Engineers-Construction Materials* 165(6) (2012) 377-384.
- [95] B.E. 1364-1, EN 1364-1: Fire resistance tests for non-loadbearing elements - Part 1: Walls., *British Standards Institute*, 2015.
- [96] T. Ashour, H. Wieland, H. Georg, F.-J. Bockisch, W. Wu, The influence of natural reinforcement fibres on insulation values of earth plaster for straw bale buildings, *Materials & Design* 31(10) (2010) 4676-4685.
- [97] J. Ren, Z. Zhao, J. Zhang, J. Wang, S. Guo, J. Sun, Study on the hygrothermal properties of a Chinese solar greenhouse with a straw block north wall, *Energy and Buildings* 193 (2019) 127-138.
- [98] H. Binici, O. Aksogan, C. Demirhan, Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials, *Sustainable Cities and Society* 20 (2016) 17-26.
- [99] M. Labat, C. Magniont, N. Oudhof, J.-E. Aubert, From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential, *Building and Environment* 97 (2016) 69-81.
- [100] Y. Brouard, N. Belayachi, D. Hoxha, N. Ranganathan, S. Méo, Mechanical and hygrothermal behavior of clay – Sunflower (*Helianthus annuus*) and rape straw (*Brassica napus*) plaster bio-composites for building insulation, *Construction and Building Materials* 161 (2018) 196-207.
- [101] B. Ismail, N. Belayachi, D. Hoxha, Optimizing performance of insulation materials based on wheat straw, lime and gypsum plaster composites using natural additives, *Construction and Building Materials* 254 (2020) 118959.
- [102] P. Mariana, N. Antonia, A. Jaume, A.M. Lacasta, Characterization of thermal insulation materials developed with crop wastes and natural binders, *WSB 14 Barcelona Sustainable Building*, 2014, pp. 188-1-188-10.
- [103] M. Palumbo, J. Formosa, A.M. Lacasta, Thermal degradation and fire behaviour of thermal insulation materials based on food crop by-products, *Construction and Building Materials* 79 (2015) 34-39.
- [104] E. Tůmová, R. Drochytka, V. Černý, P. Čada, Development of organic and biodegradable insulating material for ETICS, *Procedia engineering* 195 (2017) 81-87.
- [105] C. Rojas, M. Cea, A. Iriarte, G. Valdés, R. Navia, J.P. Cárdenas-R, Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings, *Sustainable Materials and Technologies* 20 (2019) e00102.
- [106] S. Liuzzi, C. Rubino, F. Martellotta, P. Stefanizzi, C. Casavola, G. Pappalè, Characterization of biomass-based materials for building applications: The case of straw and olive tree waste, *Industrial Crops and Products* 147 (2020) 112229.
- [107] M. Rahim, O. Douzane, A.T. Le, G. Promis, T. Langlet, Characterization and comparison of hygric

- properties of rape straw concrete and hemp concrete, *Construction and Building Materials* 102 (2016) 679-687.
- [108] N. Belayachi, D. Hoxha, I. Redikutseva, Etude Comparative du comportement hygrothermique des matériaux à base de fibres végétales, *Rencontres Universitaires de Génie Civil*, 2015.
- [109] M. Palumbo, A.M. Lacasta, N. Holcroft, A. Shea, P. Walker, Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials, *Construction and Building Materials* 124 (2016) 269-275.
- [110] S. Liuzzi, S. Rigante, F. Ruggiero, P. Stefanizzi, Straw based materials for building retrofitting and energy efficiency, *Key Engineering Materials*, Trans Tech Publ, 2016, pp. 50-63.
- [111] R.V. Ratiarisoa, C. Magniont, S. Ginestet, C. Oms, G. Escadeillas, Assessment of distilled lavender stalks as bioaggregate for building materials: Hygrothermal properties, mechanical performance and chemical interactions with mineral pozzolanic binder, *Construction and Building Materials* 124 (2016) 801-815.
- [112] M.R. Ahmad, B. Chen, M.A. Haque, S.F.A. Shah, Development of a sustainable and innovant hygrothermal bio-composite featuring the enhanced mechanical properties, *Journal of Cleaner Production* 229 (2019) 128-143.
- [113] C. Rode, R. Peuhkuri, B. Time, K. Svennberg, T. Ojanen, Moisture buffer value of building materials. *J ASTM Int* 4 (5): 100369, 2007.
- [114] C. Rode, R.H. Peuhkuri, K.K. Hansen, B. Time, K. Svennberg, J. Arfvidsson, T. Ojanen, NORDTEST project on moisture buffer value of materials, AIVC Conference 'Energy performance regulation': Ventilation in relation to the energy performance of buildings, INIVE eeg, 2005, pp. 47-52.
- [115] M.R. Ahmad, B. Chen, S.Y. Oderji, M. Mohsan, Development of a new bio-composite for building insulation and structural purpose using corn stalk and magnesium phosphate cement, *Energy and Buildings* 173 (2018) 719-733.
- [116] Y. Zuo, J. Xiao, J. Wang, W. Liu, X. Li, Y. Wu, Preparation and characterization of fire retardant straw/magnesium cement composites with an organic-inorganic network structure, *Construction and Building Materials* 171 (2018) 404-413.
- [117] B. Belhadj, M. Bederina, Z. Makhloufi, A. Goullieux, M. Quéneudec, Study of the thermal performances of an exterior wall of barley straw sand concrete in an arid environment, *Energy and Buildings* 87 (2015) 166-175.
- [118] A. Bakatovich, F. Gaspar, Composite material for thermal insulation based on moss raw material, *Construction and Building Materials* 228 (2019) 116699.
- [119] E.C. Pachla, D.B. Silva, K.J. Stein, E. Marangon, W. Chong, Sustainable application of rice husk and rice straw in cellular concrete composites, *Construction and Building Materials* 283 (2021) 122770.
- [120] J. Wang, Y. Zuo, J. Xiao, P. Li, Y. Wu, Construction of compatible interface of straw/magnesia lightweight materials by alkali treatment, *Construction and Building Materials* 228 (2019) 116712.
- [121] J. Dušek, M. Jerman, M. Podlena, M. Böhlm, R. Černý, Sustainable composite material based on surface-modified rape straw and environment-friendly adhesive, *Construction and Building Materials* 300 (2021) 124036.
- [122] M. Babenko, A. Estokova, M. Savytskyi, S. Unčik, Study of thermal properties of lightweight Insulation made of flax straw, *Slovak Journal of Civil Engineering* 26(2) (2018) 9-14.
- [123] A. Laborel-Préneron, C. Magniont, J.E. Aubert, Hygrothermal properties of unfired earth bricks: Effect of barley straw, hemp shiv and corn cob addition, *Energy and Buildings* 178 (2018) 265-278.
- [124] M. Giroudon, A. Laborel-Préneron, J.-E. Aubert, C. Magniont, Comparison of barley and lavender straws as bioaggregates in earth bricks, *Construction and Building Materials* 202 (2019) 254-265.

- [125] M. Viel, F. Collet, Y. Lecieux, M.L.M. François, V. Colson, C. Lanos, A. Hussain, M. Lawrence, Resistance to mold development assessment of bio-based building materials, *Composites Part B: Engineering* 158 (2019) 406-418.
- [126] K. Chetehouna, N. Belayachi, B. Rengel, D. Hoxha, P. Gillard, Investigation on the thermal degradation and kinetic parameters of innovative insulation materials using TGA-MS, *Applied Thermal Engineering* 81 (2015) 177-184.
- [127] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, *Sustainable Materials and Technologies* 4 (2015) 1-17.
- [128] F. D'Alessandro, F. Bianchi, G. Baldinelli, A. Rotili, S. Schiavoni, Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance, *Journal of Building Engineering* 11 (2017) 56-68.
- [129] A.D. González, Energy and carbon embodied in straw and clay wall blocks produced locally in the Andean Patagonia, *Energy and Buildings* 70 (2014) 15-22.
- [130] C. Bories, E. Vedrenne, A. Paulhe-Massol, G. Vilarem, C. Sablayrolles, Development of porous fired clay bricks with bio-based additives: Study of the environmental impacts by Life Cycle Assessment (LCA), *Construction and Building Materials* 125 (2016) 1142-1151.
- [131] A. Quintana-Gallardo, J.R. Clausell, I. Guillén-Guillamón, F.A. Mendiguchia, Waste valorization of rice straw as a building material in Valencia and its implications for local and global ecosystems, *Journal of Cleaner Production* 318 (2021) 128507.
- [132] S. Cascone, F. Catania, A. Gagliano, G. Sciuto, Energy performance and environmental and economic assessment of the platform frame system with compressed straw, *Energy and Buildings* 166 (2018) 83-92.
- [133] V. Zieger, T. Lecompte, A.H. de Menibus, Impact of GHGs temporal dynamics on the GWP assessment of building materials: A case study on bio-based and non-bio-based walls, *Building and Environment* 185 (2020) 107210.