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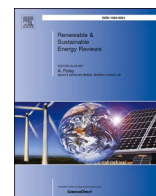
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Sustainability of biomass-based insulation materials in buildings: Current status in France, end-of-life projections and energy recovery potentials

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ABSTRACT

Concerns over climate change have driven the decarbonization of the building sector, the largest energy consumer in France. This consumption is primarily dedicated to heating and cooling. Thermal insulation in construction plays an important role in the minimization of operational energy consumption. Currently, insulation is performed via mineral and fossil-derived materials, which require high manufacturing energy. For this reason, attention has been paid to finding clean and energy-efficient alternatives. Subsequently, biomass-based insulation materials have been identified as low-embodied energy materials that reduce energy use and greenhouse gas emissions. These green and sustainable insulation materials fall in line with the transition in France towards low-carbon and positive-energy buildings. In this respect, research works have mostly focused on renewable biomass resources and wastes, the design and production of insulation materials, the testing of their properties and their installation in buildings; however, few articles have reviewed their durability and end-of-life management. To fit more in the circular bioeconomy concept, light has been shed in this review on the end-of-life of these biomaterials to avoid their landfilling. Therefore, this review provides a state-of-the-art of the different bio-based building products commercialized in France, with a forecast of their volumes and waste deposits by 2050. Furthermore, this study explores waste management strategies, focusing on waste-to-energy routes, which are revealed to be the most promising. The energy recovery from bio-based insulation wastes expected in 2050 saves 4.1 million m³ of land, 75,000 tons of fossil fuels and 89 million euros while avoiding the rejection of 312,771 tCO₂eq.

1. Introduction

Over the last decades, energy consumption in the construction industry has increased worldwide due to industrialization, urbanization, and population growth, thus increasing the demand for energy derived from fossil fuels [1]. Aside from being energy-intensive, this sector is considered resource-intensive and wasteful in the European Union (EU). The burning of non-renewable resources along with waste landfilling has drastically accumulated huge quantities of greenhouse gases (GHGs), accentuating global warming and climate change [2].

In France, the building sector, which includes residential and tertiary buildings, is currently the predominant energy-consuming sector. In 2018, approximately 63 million tons of oil equivalent (toe) were consumed for the sole use of buildings, corresponding to 45% of the national final energy consumption [3,4]. The latter is expected to increase due to population growth and the emergent need for household

appliances and indoor thermal comfort [5]. Moreover, the building sector is the second-largest emitter of GHGs following the transportation sector; hence it is a main contributor to global warming. Greater than 123 million tons of carbon dioxide (tCO₂) per year [6] are emitted by the residential and tertiary sectors combined, accounting for almost 28% of the national CO₂ emissions [7]. Above and beyond, the building sector in France generates 46 million tons of waste per year, representing nearly 15% of the total national production. These heterogeneous wastes include 75% inert wastes, 23% non-hazardous non-inert wastes and 2% hazardous wastes [8]. More than 90% of these wastes are derived from demolition and renovation, while only 7% arise from new construction [9,10].

Recently, environmental sustainability has been considered a strategic approach that acts as a barrier against the over-exploitation of natural resources, energy consumption, pollutant emissions and waste generation [9]. Thus, the Energy Transition Act for Green Growth (ETAGG), promulgated in 2015, has fixed stringent objectives for

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List of abbreviations

ACERMI	Association for Certification of Insulating materials
AGR	Annual growth rate
ATec	Technical Assessment
3BMs	Bio-based building materials
EC	Environmental Code
EPDs	Environment Product Declarations
EoL	End-of-Life
ETAGG	Energy Transition Act for Green Growth
EU	European Union
FRs	Flame retardants
FU	Functional Unit
GHGs	Greenhouse gases
GWP	Global Warming Potential
LCAs	Life cycle assessments
LHV	Lower heating value
MEST	Ministry of Ecological and Solidarity Transition
MDF	Medium-density fiberboards

NO _x	nitrogen oxides
PE	Polyethylene
PP	Polypropylene
PUR	Polyurethane
PRSC	Professional rules of straw construction
R	Thermal resistance coefficient
RBR	Responsible Building Regulation
RE	environmental regulation
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
RT	thermal regulation
SO _x	sulfur oxides
t _{CO2eq}	tons of CO ₂ equivalent
toe	tons of oil equivalent
VOCs	Volatile Organic Compounds
WFC	wood-frame construction
WPCs	wood-plastic composites
WTE	Waste-to-Energy

decreasing energy consumption, GHG emissions and waste. Energy consumption is set to decline by 50% between 2012 and 2050. The share of GHGs is expected to be reduced by 75% in 2050 compared to 1990. The waste recycling rate has to reach 55% while reducing 50% of non-recycled waste by 2025 and promoting thermochemical conversion [10].

While reasoning in “cradle-to-grave” approach for the life cycle assessments (LCAs) of a building, the environmental impacts emanate mainly from the operational energy (hot water, lighting, air conditioning, heating, ...) [11] and the embodied energy (materials manufacturing, transport, disposal, ...) [12,13]. To reduce energy consumption, the thermal performance of new and old buildings has to be improved to limit their energy requirements. The insulation of the building envelope was determined to be an effective solution for operational energy saving [14,15], primarily in terms of the reduction of cold and heat losses [5]. Besides, great attention has been dedicated to the substitution of conventional insulation materials with low embodied energy materials in line with the transition of France towards a “green and sustainable economy” [16]. Therefore, more environmentally-friendly materials derived from forestry, agriculture and recycling have been designed for GHGs mitigation [17,18]. Currently, about 230,000 tons of biomass produced in France are valorized in the building sector, storing each 1.8 t_{CO2eq} (t_{CO2eq}) [19]. Consequently, 425,000 round trips Paris-New York per year are avoided from the sole use of renewable biomass in French buildings [20].

The development history of biomass-based materials began in France in the 2000s. The concept of bio-based materials was introduced in the decree of December 19, 2012, relating to the content and the conditions of attribution of the “bio-based building” label [21], in harmony with the EU regulation n° 305/2011. Accordingly, a bio-based material is delineated as a “material resulting from plant or animal biomass that can be used as a raw material in construction and decoration products, fixed furniture and as a construction material in a building” [21]. However, there is no specific rule regarding the bio-based share within a product [22]. Bio-based materials provide an extensive range of possible products such as structural wood or timber, paints, varnishes, adhesives, insulation and finishing products [23]. The latter can be used in several applications, particularly in the building and automotive industries. In this review, the term bio-based building materials (3BMs) refers only to insulating and finishing materials derived from biomass [24]. Structural wood was excluded from this study because its material/energy recovery has been extensively examined in the literature owing to its

sufficient tonnage at End-of-Life (EoL) [25,26]. Wood is recycled into mulch, particleboards, paper pulp, chipboards, engineered boards, and composites [25,27,28] or burned in industrial boilers for heat generation [26,28].

Standing in the heart of the challenges of sustainable construction, 3BMs constitute one of the answers for the climatic emergency and the development of a circular economy. Their integration rate in construction and renovation has reached 10% by 2020. The new environmental regulation “RE 2020” strongly encourages the use of 3BMs. Their market share is expected to reach 13%, along with a reduction of 30%–40% of CO₂ by 2030. The incentive to use these materials will lead to increased volumes of waste to be treated at the EoL as their average working life fluctuates between 20 and 50 years [29,30]. At present, the recovery scenarios are almost non-existent, and the default scenario considered in LCAs and Environmental Product Declarations (EPDs) is landfilling. This inefficient option is designated as the least desirable in the Waste Management hierarchy [31] as being always applied without environmental protection measures [32]. The first deposits, comprising between 5000 and 15,000 tons, are expected to appear between 2025 and 2030 [29,30]. Starting from this date, 3BMs waste generation will increase exponentially to reach 150,000 tons by 2050, requiring the prioritization of their fate [32]. The reuse and recycling of 3BMs encounter technical, economic and environmental obstacles [33,34]. Consequently, energy recovery is considered to be the most efficient waste treatment option leading to the strategic production of added-value products. Moreover, the integrated waste biorefinery concept should be promoted to target the treatment of multiple and mixed feedstocks for the production of heat, power, biofuels, materials together with platform chemicals.

Most of the research works on 3BMs have mostly focused on the production [14,33,35,36] and performance testing of these products [29,37,38], but few have reviewed their durability [34,39,40] and final disposal. The EoL phase appears to be neglected and requires excessive attention when performing LCAs. Therefore, the novelty of this work resides in going beyond the manufacturing and use phases and sheds light on the EoL of biomaterials commercialized in France, to fit more in the circular economy concept. In addition, this review aims to explore and evaluate the different waste management strategies, including reuse, recycling and energy recovery, for the valorization of 3BMs at their EoL in a circular economy context. However, prior to assessing a corresponding waste management scenario, the methodology consists of understanding the origin, composition, amount and the flows of the generated waste. For that, section 2 provides a state-of-the-art of the

existing 3BMs in France. Section 3 describes the potential recovery routes for the management of 3BMs wastes. Section 4 presents the fate of the additives and their effects on the selection of the recovery routes. Finally, the final section highlights the main conclusions of this study.

2. Bio-based building materials used in France

The utilization of biomass resources for bioenergy applications, including household heating, has been adopted worldwide for several decades. However, in the 20th century, the planet shifted from a biomass-based economy to a fossil-fuel economy. Due to this swing, huge CO₂ quantities have been produced accentuating climate change and growing the depletion of non-renewable resources. During this period, agricultural production and policies have been put in place in some countries banning the burning in situ of primary resources; hence, agro-residues become abundantly available, thus necessitating new markets and proper applications. In the framework of sustainable development, EU rules have stimulated the re-deployment of the bio-based economy as a key strategy for the mitigation of environmental risks [41]. Manufacturers of construction materials were also involved in the environmental awareness, prompting the valorization of renewable raw materials for energy and resource savings. The conversion of sustainable resources into construction and thermal/acoustic insulation products has become a subject of growing interest in all EU countries due to the rise of awareness about environmental problems [5]. In the 21st century, the bio-insulating material sector has experienced relatively recent development in France [42].

2.1. Raw materials origin

The bio-based materials/products (Fig. 1), mainly applied in building insulation and finishing, are derived from:

- Agricultural residues and plant fibers such as hemp [43,44], flax [45, 46], cereal straws [47,48] and husks [49].
- Forestry wastes such as cork [50,51] and wood chips/shavings/fibers [14,39].

- Animal by-products such as sheep wool and duck feathers.
- Recycled materials indirectly coming from forestry and agriculture [24] such as newspapers/cardboards [52] and textile wastes [5,53, 54].

Table 1 reviews the raw materials, the main processing steps required for manufacturing and the implementation techniques of the final products.

2.1.1. Agricultural residues and plant-fibers

2.1.1.1. Cereals straw. In 2018, the surface area of farms has been estimated to be 26.8 million hectares (ha) of utilized agricultural area, equivalent to 49% of the Metropolitan France area [55,56]. Around 9.1 million ha were devoted to the cultivation of cereals (including wheat, barley, maize, sorghum and oats) for grains in 2018 [55], which may point toward a high availability of straw. Predominantly, the wheat straw is recycled for construction since this cereal is the utmost grown crop on the French territory, representing 58% of the cereal cultivation area. The professional rules of straw construction (PRSC) recommend the use of straw bales for frameworks and insulation [57]. Based on the National Biomass Observatory, 55% of the straw is returned to the ground every year for agricultural purposes. The remaining volume available is depicted to be around 24.5 million tons (Mt) of dry matter per year, out of which 22.7 Mt are used for livestock farming and animal bedding and 1.7 Mt can be exploited for new applications [58,59]. In 2016, the French straw construction network estimated that only 4600 tons of straw were mobilized in the construction sector. The market growth potential of straw bales is substantial because the available deposit may build about 170,000 buildings per year [58].

2.1.1.2. Flax. France is the leading flax-producing country in Europe. The surface area dedicated to the cultivation of the two species of “*Linum usitatissimum*” accounted for nearly 98,263 ha in 2017. The main products of flax are long fibers intended for clothing, home textiles and decoration. The planted area and prices evolve with the demands of the

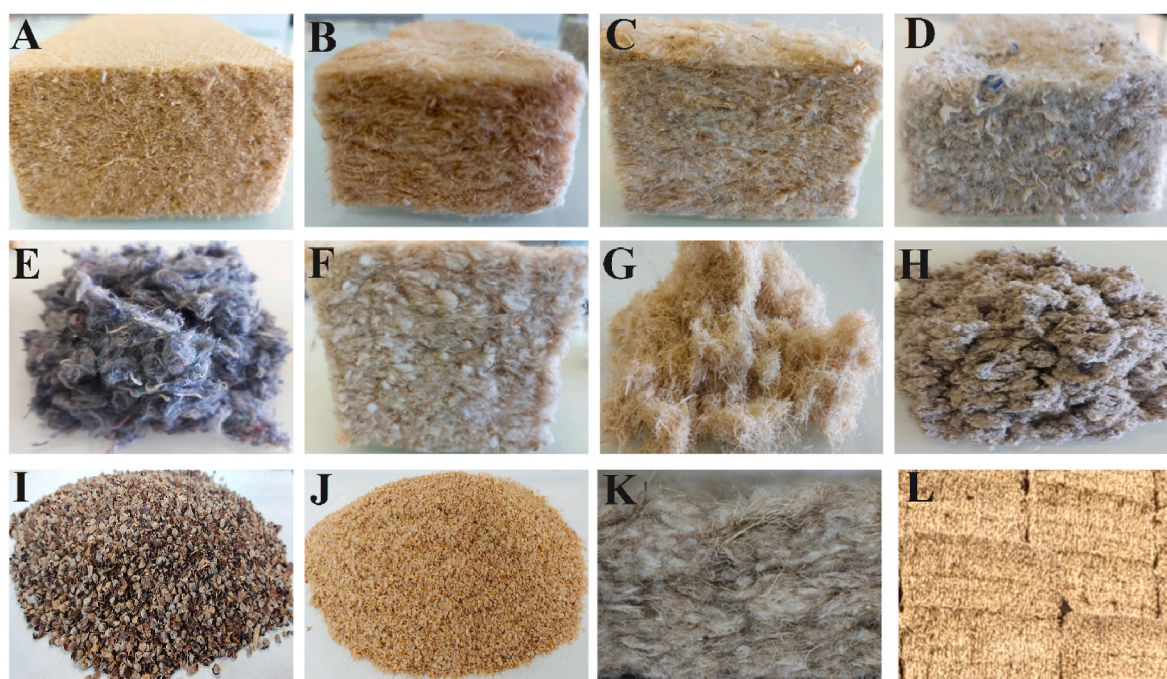


Fig. 1. Various biomass-based insulation materials and products: A) Wood hardboards B) Wood medium-density fiberboard C) Hemp panel D) Cellulose wadding panel E) Recycled textiles in loose-fill F) Mixed fibers (cotton/flax/hemp) panel G) Hemp fibers H) Cellulose wadding in loose-fill I) Buckwheat husks J) Millet husks K) Flax panel L) Wheat straw bales.

Table 1
From raw materials to products manufacturing and implementation techniques [58,60].

Raw material		Feedstock	First processing step	Second processing step	Products	Implementation techniques	
Agricultural residues and plant-fibers	Cereals (wheat)	1.7 Mt/year available and recoverable straw	Grubbing up and tedding	–	Straw bales	Installation	
				Mixing with earth	Earth-straw	Installation	
	Flax	350,000 t/year of straw	Defibering and separation of long fibers	Bending with strong cardboard and urea-formaldehyde glue, hot-pressing, cooling and cutting	Straw panels		
				Mixing of shives with wood	Flax/wood agglomerated panels	Installation	
	Hemp	100,000 t/year straw available	Defibering	Mixing of short fibers with additives and/or other bio-based or synthetic fibers	Floor underlayment	Installation, filling and/or manual or mechanical projection (blowing)	
				Coating or mixing of fibers with polyesters and additives and pressing	Dry process		Flax wool (panels/rolls)
							Hemp fibers in loose-fill
							Hemp wool (panels/rolls)
	Husks	12,000 t/year available	Husking of grains		Plastic composites	Spraying by pouring and blowing	
							Floor underlays
					Concrete, mortar and coatings		
					Prefabricated elements (concrete blocks, walls)		
Forestry waste	Cork	2500 t/year	Grinding	Mixing of hemp shives with aerial lime, hydraulic lime or clay	Concrete, mortar and coatings	Blowing	
							Prefabricated elements (concrete blocks, walls)
	Cork	2500 t/year	Grinding	Sprinkling of hydrated lime under and on the husk	Rice husks in loose-fill	Blowing	
				–	Cork granules or pellets		
	Wood	8.3 Mt/year of sawmills wastes	Manufacturing of cork for wine bottling	Wet process	100% cork panels	Installation or blowing	
				Dry process (addition of a binder)	Cork panels		
				Milling into wood chips	Wood pellets in bulk		
				Mixing of wood chips with lime	Wood concrete		
Wood waste products		Sawing, slicing and peeling or pulping for the creation of laminated panels, plywood and wood-based products	Screening, –	Wood fibers in bulk			
			defibering into wood fibers and mixing with polyesters	Dry process		Medium-density fiberboards	
				Wet process		High-density fiberboards	
						Wood-plastic composites	
Forest chips			Mixing with plastics and extrusion	Wood-plastic composites			
Animal by-products	Sheep wool	14,000 t/year wool available	Sorting of wool grease, washing and treatment	Bending with hot-melt fibers and shaping	Sheep wool (panels and rolls)	Installation	
				–	Sheep wool in loose-fill	Blowing	
Recycled materials	Cellulose wadding	1 Mt/year of journal papers and 0.9 Mt of cardboards	Crushing, sorting, refining and mixing with additives	Carding and packaging	Cellulose wadding in loose-fill	Pouring, blowing, injection or projection	
				Mixing with other bio-based fibers or synthetic fibers as reinforcement	Cellulose wadding panels	Installation	
	Recycled textile	624,000 t/year textiles waste	Shredding and treatment	Bending with hot-melt fibers and shaping	Recycled textiles (panels and rolls)	Installation	
				–	Recycled textiles in loose-fill	Blowing	

Chinese textile sector, the principal consumer. The flax by-products, short fibers and flax shives, are mainly recycled in the paper and construction industries. Based on 6 tons of straw/ha, nearly 10% of short fibers and 45% of shives were obtained. These proportions are equivalent to an annual production of 59,000 and 265,000 tons, respectively. A study conducted by the Ministry of Ecological and Solidarity Transition (MEST) states that only 1% of fibers and 50% of shives are recycled into flax insulating wool and chipboards [60].

2.1.1.3. Hemp. For millennia, hemp or “Cannabis Sativa” was grown for its valorization in the marine, paper and textile industries [36]. In the 1970s, this crop was mainly introduced in the construction sector due to the disappearance of sailing boats and the competition in the textile industry by synthetic fibers. France is positioned as the largest hemp-growing country in Europe with a cultivation surface of 16,400 ha in 2017, which is half of the European planted area [61]. The harvesting yields of 1 ha reach 1 ton of seeds and 7 tons of straw. The seeds can be

used as fishing baits, for feeding birds, in human food and cosmetics [36]. The straw, representing 79% of the economic value of this crop, is mechanically defibered into 25% of long bast fibers and 43% of shives (woody short core fibers). The production of hemp-based building materials ensures the recycling of 29% of the fibers and 14% of the shives [58,61]. The fibers undergo a second transformation to constitute insulating panels and rolls, while the non-fibrous shives are mixed with lime or cement binders for the manufacturing of light mortar or concrete [58].

2.1.1.4. Husks. The husk is the hard external layer protecting some cereal grains such as rice, spelt, buckwheat, oats and millet. In France, the cultivation area of rice and spelt represented about 15,065 and 12,000 ha, respectively, in 2016 [58]. Buckwheat and oats accounted for 5000 and 91,831 ha in 2018 according to annual agricultural statistics. Unlike the other cereals, these grains remain coated during harvesting and need to be decorticated in the processing plant to isolate the husk

from the grain. This husk is rich in silica and lignin and constitutes about 20% of the weight of the grain [62]. The availability and low price of husks have made them attractive for animal bedding, land fertilizing and combustion [58]. More recently, the market for these by-products in the construction sector is growing as a building (lightweight concrete) and insulation material (in raw form) [63,64].

2.1.2. Forestry wastes

2.1.2.1. Cork. According to the French Cork Federation, the annual production of oak cork is around 2500 tons, for worldwide production of around 254,000 tons per year [60]. The cork is separated into black cork granulates and white cork granulates. The first one is obtained after a primary debarking of the 25 years old oak tree. Known also as male cork, the black cork granulates are usually hard and have an irregular structure deprived of elasticity. As being complicated to handle and process, the black cork granulates are used for floor covering and thermal insulation [51,65]. Nine years after debarking, white cork granulates (female cork) are formed, hence clarifying their higher market price [66]. Owing to their elasticity and cellular structure, their application is dedicated to wine bottling due to their ability to expand and tightly seal the bottle after their insertion [67]. It is estimated that 3 tons of male cork give 1 ton of agglomerated or granulated expanded cork [68], i.e. 800 tons per year for insulation. In France, almost all 100% cork-based building panels are imported from Portugal [60].

2.1.2.2. Wood-derived products. The surface area of forests available for wood supply was 16.8 million ha in 2019, accordingly 31% of the French territory [69]. Around 38.9 million m³ of wood were harvested and commercialized in 2018 for structural (51%), industrial (27%) and energy purposes (22%). Structural and energy wood are not included in the scope of this study. Only the wood-derived products used for the manufacturing of insulation materials are considered in this review.

The wood used for the manufacturing of insulation boards and granulates originate from forestry chips and cuttings, sawdusts of the logging process, wood-based products at their EoL (carpentry, furniture) and waste from local sawmills (8.3 Mt in 2018 [70]). That have been reduced to a fibrous state. Besides, round wood logs may be debarked, chipped, steamed and then refined through a defibrator to produce wood fibers. Subsequently, the fibers can undergo a “dry” process or a “wet” process. In the former process, the fibers are exposed to steam and pressure (0.6–1 MPa), then mixed with additives and resins prior to being hot-pressed to produce medium-density fiberboards (MDF). In the latter process, the fibers are washed with water without adhesives, then pressed or hot pressed and dried to form softboards (200–400 kg/m³) and hardboards (>900 kg/m³) [71].

2.1.3. Animal by-products

In 2018, the French sheep population stood at nearly 7 million head [72,73]. It is estimated that 2 kg of wool grease are produced per head, hence leading to around 14,000 tons of wool. Based on the interviews conducted by the MEST, 15% of the tonnage is used for the textile industry while the residual part is valorized as a construction material [60]. Generally, the wool is exported to China for low-cost washing [74]. Owing to the Covid-19 pandemic, exportation was not possible, hence leading to additional costs.

2.1.4. Recycled materials

The manufacture of cellulose wadding and recycled textiles does not require direct agricultural production, but the recycling of newspapers and cotton waste, respectively.

2.1.4.1. Cellulose wadding. In France, 6.96 Mt of papers, newspapers and cardboard were collected in 2018, 79.2% of which were recycled for packaging, graphic uses, toilet and tissue papers. The non-recycled

part is used for industrial, building and special applications [75]. The newspapers are first sorted for clips and plastics removal. Then, they are shredded into small pieces (2–4 cm) prior to going through a fiberizer which will be finely milled into flakes [52].

2.1.4.2. Recycled textiles. Similarly, woven fabric wastes at their EoL can be shredded to become, all over again, a raw material. In 2018, the marketed items were assessed to be 624,000 tons; merely 38% were collected. After sorting, 58.6% can be reused as secondhand products whereas 10% are recycled as wipers and 22.6% as materials for gartening. This latter fraction can be used for the production of new textiles, composite, automotive and building insulation materials. However, the non-recyclable fraction is subjected to energy recovery (8% as solid recovered fuel and 0.4% incineration with energy recovery) while the remaining part is dumped in landfills [76].

With the current strategy to boost the building's sustainability, natural resources have appeared in the market as construction alternatives. Agricultural straws have a low thermal conductivity, low density and low cost owing to their hollow structure. There is an increasing demand for straws for insulation but not easily quantifiable. The production of hemp is anchored in France in line with the intention to diversify the market of this crop. Recently, the hemp sector is subjected to the competition of the automotive sector [58]. Wood-derived products are characterized by a significant volume of available resources. The manufacturing of wood-based insulation panels is energy-intensive. Regarding the flax, insulation materials add value to the less noble fraction of the plant [45]. The cellulose wadding and textiles materials originate from recycled products, hence boosting the circular economy. On the other hand, these materials already comprise inks and dyes, leading to gaseous contaminants [77].

2.2. Benefits and drawbacks

In 2013, the Ministry of Ecology, more particularly by the General Commission for Sustainable Development, has identified the 3BMs sector as one of the 18 green strategic sectors with high economic development potential creating several tens of thousands of direct and indirect jobs. In 2015, Article 14 of the ETAGG has stipulated the use of renewable and sustainable materials based on biomass for insulation purposes. This is particularly because of their role in reducing the consumption of fossil raw materials and mineral resources [77], limiting GHG emissions via the storage of atmospheric carbon during the building life cycle [78], recycling abundant and renewable and locally available biomass resources, saving energy in buildings [79] and creating new economic sectors [80]. Besides, these materials have low embodied energy; for instance, cellulose wadding consumes 20 times less energy than polyurethane (PUR) [81]. The low-density wood boards and hemp wool panels consume one-third and half of the energy of PUR (115 kWh/m²), respectively. Furthermore, bio-insulations such as cellulose wadding, hemp, and expanded cork guarantee a good thermal performance allowing a significant thermal day/night phase shift for summer comfort [82]. Indeed, the thermal conductivity coefficient is between 0.035 and 0.051 W/(m.K) for eco-materials against 0.030 and 0.042 W/(m.K) for conventional insulation. Moreover, biomaterials exhibit very good hygrothermal behavior regulating temperature and indoor humidity [83]. The water absorption of hemp and sheep wool is, respectively, 10 and 30 times higher than that of conventional insulations. In addition, the bio-based sector triggers high innovation prospects and strong potential for the development of local industries [80] (150 million euros invested and 600 million euros of additional revenues) and local jobs (4000 jobs). Additionally, bio-based products deprived of additives can be recycled or reused for new applications (second life), composted, biodegraded, converted to energy or land-filled. Unlike polyurethane, straw can be simply composted after selective deconstruction [84].

Despite their good thermal and acoustic performance, a higher thickness of 30 cm of biomass-based insulation materials is needed compared to 20 cm of conventional materials to provide the same thermal resistance [85]. Although their sustainability, their availability on the insulation market is discrete with a share of only 10% [58], contrary to mineral (50%) and petroleum-based (40%) materials. This is due to the limited raw biomass resources and their higher cost [86]. Notwithstanding their ecological advantages, these bio-insulations are not 100% based on biomass as the majority may enclose up to 15 wt% of additives (fire retardants, antifungal agents, water repellents, ...) [77] and about 15 wt% of non-biodegradable binders (polypropylene PP, polyethylene PE, polyesters, ...) [87]. These chemicals result in Volatile Organic Compounds (VOCs) emissions, such as formaldehyde, leading to indoor air pollution [37,88,89]. Besides, agricultural residues may be transported for 50 and 100 km to be processed, which impacts negatively the environment [77].

Due to their intrinsic properties summarized in Fig. 2, the use of bio-based materials is encouraged by Europeans, including French, public authorities, as they fit perfectly into the sustainable development approach. Nevertheless, the local and least possible processed bio-based materials have to be favored to meet the characteristics for which they are put into action; thus reaching the sustainable construction goal [77].

2.3. Application in buildings

Several types of bio-based insulation products have been commercialized on the French market. These can be applied in new constructions as in renovation. The products are manufactured in various forms depending on the insulated space and the intended application. The three largest types of applications and the associated products are shortened in Table 2.

The 3BMs are classified as “standalone” insulation if fabricated using one simple material or “hybrid” if consisting of two or more natural fibers (multi-layer) [5]. Bio-based building materials can perform the same function and the same material can carry out, simultaneously, several functions [29]. Straw bales and wood-based concrete blocks are used in the building for wall filling and insulation purposes [90]. The loose-fill insulation is either blown into internal wall cavities or spread on the attic spaces to fill the gaps between the joists. Rolls, panels, rigid

and semi-rigid boards are mainly dedicated to internal insulation. When coated with plaster, they can be used for external insulation. Lightweight cementitious materials are non-structural components used as insulating infill in walls supporting and casting around the building frame [91]. The interior design products are only used for finishing applications; for instance, linoleum is applied for floor covering. Wood-plastic composites (WPCs) are used for fencing, cladding and decking [92].

In France, prior to marketing, the technical properties of 3BMs are tested and evaluated. They must comply with the European Construction Product Directive to be commercialized on the local market while they must hold a European technical approval for being placed on the European market. Since 2008, innovative bio-based insulating materials manufactured in France have to possess a qualification certificate issued by the Association for Certification of Insulating Materials (ACERMI). This ACERMI certification guarantees the conformity of the product with the thermal characteristics stated on the label. Besides the certificate, a Technical Application Document and a Technical Assessment (ATec) have to be formulated for each material by a specialized group and issued by the Commission in Charge for Formulating Technical Assessments.

2.4. Classification and composition

Bio-based building products are composed of cellulosic biomass (granulates, fibers, wool, shives, ...) forming the bulk of the volume, a binder (synthetic or mineral) and additives (organic or inorganic) [53]. The latter are added to improve the properties, and hence the durability, efficiency and performance of building materials are enhanced. They ensure several functions such as flame retardants (FRs), water repellents and biocides or fungicides. The additives must comply with EU regulations such as the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation to avoid threatening human health and the environment.

The 3BMs composition depends on the manufacturer, insulation form and intended use. The relative percentage of each constituent used, principally the additives, is likely to differ considerably between the manufacturers of the same product. Frequently, for confidentiality reasons, little information is provided on the exact formulations

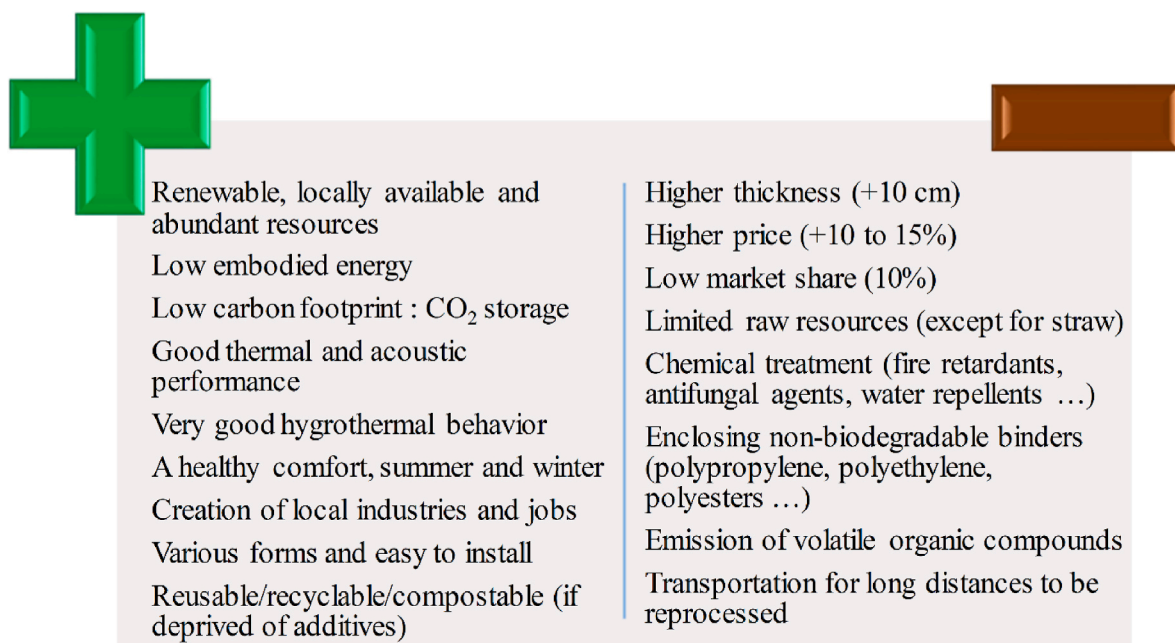


Fig. 2. Advantages and disadvantages of biomass-based materials.

Table 2

The bio-based insulation products and their application in the building [58,60,85].

Bio-based building material	Applied (added) insulation		Distributed insulation, filling products and façade (wall) finishing		Floor/wall coating (composites)
	Internal insulation (roofs, walls, floors)	External insulation	Floors and basement	Walls	Carpentry, interior and exterior fittings
Cellulose wadding	Loose-fill Flexible panels Composites boards (hemp/wood/flax)		Loose-fill fibers	Concrete block ^a	
Wood-based products	High and medium density fiberboards Bulk fibers Composite boards (wood fibers/glass wool)	High-density fiberboards Plaster coating	Loose-fill (aggregates)	Wood-concrete block	Wood-plastic composites (decking, cladding ...) Fire-resistant boards
Straw (cereals and rice)	Compressed rigid panels			Wheat straw bales Earth/straw coating Earth/straw/lime coating	
Hemp	Flexible panels/rolls Loose-fill hemp fibers Composite panels (flax/wood/cotton)	Hemp plaster/render	Loose-fill hemp fibers Hempcrete (lime/hemp)	Hemp block masonry Hempcrete	Reinforced plastic/decking Thin acoustic underlays
Recycled textiles	Soft boards/rolls Bulk		Loose-fill fibers	Concrete block ^a	
Sheep's wool	Soft boards Rolls Bulk wool				
Flax	Flax wool (panels/rolls)			Flax mortar and concrete ^a	Particleboards Linoleum Acoustic underlays
Cork		Expanded rigid cork agglomerates (no resins)	Loose-fill granulated cork	Cork cladding Granulated cork/hydraulic lime	Cork agglomerates composites (with resins) Underlays
Husks	Loose-fill Thermo-bonded husk panels ^a			Rice husk-earth based composites Husks/lime concrete ^a	
Miscanthus				Mortar and plant-based concrete ^a	Agglomerated panels or chipboards ^a

^a Products under development.

(proportion and chemical name) of the incorporated additives in the end-product. The biomass content is almost 100% when the product is in loose-fill (except for cellulose wadding and recycled textiles), this share decreases to 85–90% when the product is in panels or rolls owing to the addition of synthetic binders. The bio-based content is slightly reduced in mortars, plasters and concrete (<80%) and falls to less than 50% for WPCs. The amount of additives and binders is low for internal/external insulation applications, whereas it is significantly higher for outdoor applications.

In terms of composition, the bio-sourced materials can be classified into four large different families depending on their additive content: without additives, low (<5 wt%), high (5–15 wt%) and very high (>15 wt%). Table 3 summarizes the composition of these main bio-based families marketed in France, as described in their corresponding ATec documents. Products with unknown additive content are considered to belong to the “products with low additive content” family. Furthermore, when the same product is manufactured by different industries, the average values or ranges of biomass, binders and additives are presented.

The composition of 3BMs, in terms of the amount and nature of additives, must be identified before the assessment of the EoL strategy (reuse, material or energy recovery) and the management of the generated wastes [93]. No EoL problems are associated with products deprived of additives. They can be recycled, composted or incinerated. The EoL scenarios of low and high additive content products are challenging and depend on the properties of their constituents and processing level [94,95]. The EoL of WPCs is a sensitive issue owing to the high degree of mixing along with the numerous chemicals included, rendering the separation extremely complicated [96]. Besides, the use of recycled plastics in the manufacture of WPCs can significantly reduce the number of cycles of their reuse/recycling [97].

2.5. Current market shares and future commercialized volumes

The market share of bio-based insulation materials was 6% in 2012 [60]. Due to population increase, the building stock and new constructions will be subsequently increasing. Therefore, thermal regulation (RT 2012) and RE 2020 came into force to impose stringent goals for the construction of energy-efficient buildings in agreement with “Low-energy buildings” and “Positive energy building” concepts. Besides, the pace of renovation/rehabilitation is accelerated owing to the evolution of the EU and French regulations, more specifically the home energy renovation plan that has fixed the achievement of the energy renovation of 500,000 housing per year in France, starting by 2017, via enhancing the use of bio-based materials. These regulations explain the increase in the volume of bio-based insulation products manufactured, distributed and commercialized on the French market over years. The market share became 8% in 2017 [58] and it is expected to attain 10% in 2020 and 13% in 2030; owing to RE 2020 and Responsible Building Regulation (RBR 2020) that will come into force in 2021. The cellulose wadding and the wood-based products account respectively for 40% and 50% of the bio-based insulation market share [120]. The past, current and future prospective volumes of bio-based products marketed (including importation and exportation) on the French territory are reported in Table 4. The commercialized volumes in 2020 and 2030 are calculated based on retained annual growth rate (AGR) [121,122] for the time frame 2010–2020 and 2020–2030. An AGR of 10% was associated with the main 3BMs over the last 4 years owing to the accelerated expansion of the sector in France over the last ten years. Volumes marketed have been growing steadily for more than 4 years, particularly for insulation materials. The growth rates were obtained from the data collected from the different associations representing the sectors. On the other hand, the marketed tonnages in 2050 were provided by the TERRACREA project

Table 3
Composition of main bio-based building products commercialized in France.

Family	Bio-based building product	Biomass content (wt%) $\pm 5\%$	Binder content (wt%) $\pm 2\%$	Additive content (wt%) $\pm 0.5\%$	References
Raw products	Wheat Straw bales	100%	No binder	–	[58,98]
	Expanded cork panels	100% cork	2 polypropylene strings Suberin (cork oak)	–	[60]
Products with low additive content	Cork granules in loose-fill		No binder		
	High density cork panels	95% cork	5% polyurethane resin		
	Wood granulates in bulk	<100% wood	No binder	Calcium silicate ^a	[58]
	Compressed rice straw panels	90–92% rice straw fibers	Strong cardboard ^a Urea-formaldehyde glue ^a 8–10% hot-melt polyester	Flame retardant, anti-mold and insecticide ^a	[58,99]
	Hemp shives in loose-fill	100% hemp granulates	–	0.2% anticryptogamic ^a	[100]
	Hemp boards	90% hemp fibers	<10% PE, polylactic acid or maize starch binder	0.2% anticryptogamic ^a	[100]
	Flax wool	85–100% flax	0–15% polylactic acid	Boron salts ^a Calcium silicate ^a	[58]
	Sheep wool soft boards	80–90% sheep wool	12–15% polyester or PP	Boron salts ^a Anti-moth treatment ^a KONSERVAN P10 (Permethrin) Pyrethroid-compound	[60]
	Flax soft boards	76% hemp/14% flax fiber/10% oilseed flax	Unknown ^a	Unknown ^a	[58]
	Wood Medium-density fiberboards	90% wood fibers 85% wood fibers	8.7% recycled polyester 7% polyolefin fibers	1.3% anticryptogamic ^a 8% ammonium phosphate (fire retardant)	[101] [102,103]
	Wood high-density fiberboards	82.8% wood fibers 6.3% of recycled papers	6% water 1.2% anti-slip glue (polyurethane, lignin resin, sodium silicate or paraffin) 1.3% polyolefins (PE, PP)	2.4% aluminum silicate 0.1% unknown ^a	[104,105]
	Hemp/flax/textile	91 (± 2) % fibers: 33.5% hemp 33.5% flax 33.5% cotton	9 (± 2) % polyester fibers	<1% antifungal treatment (0.2% 2-Octyl-2H-isothiazole-3-one)	[106]
	Wood concrete block	80% wood granulates	20% cement or hydraulic lime	Calcium silicate ^a	[58]
	Cob	Straw ^a	Clay earth and/or lime ^a	–	[58]
	Hempcrete	34% hemp hurds	66% metakaolin and lime	–	[107]
Products with high additive content	Cellulose/cotton	60% recycled papers	15% polyester	–	[100]
	Cellulose/hemp	20–25% hemp/flax shives/cotton			
	Cellulose/flax				
	Hemp/flax composites	44% hemp fibers 44% flax fibers	<12% polyester	0.67% 2-Octyl-2H-isothiazole-3-one	[108]
	Rice husk in loose-fill	Rice husk ^a	Unknown ^a	3% boron salts	[109]
	Loose-fill cellulose wadding	90 (± 3) % journal papers	–	3 (± 0.5) % boric acid 7 (± 1.5) % magnesium sulfate	[110]
		89 (± 1.5) % journal papers	–	4.4 (± 1) % boric acid 6.6 (± 1) % magnesium sulfate	[111,112]
	Recycled textile (panels/rolls)	75 (± 5) % cotton fibers (wool and acrylic)	15 (± 2) % bi-component polyester fibers	0.8 (± 0.2) % antibacterial 10 (± 2) % flame retardant (no boron or ammonium salts) ^a	[113]
		80% cotton fibers	20% bi-component polyester fibers (hot melt)	Unknown ^a	[114]
	Recycled textile in loose-fill	89.2 (± 2.2) % textile fibers with a cotton majority (>70%), polyester and acrylic fibers	–	10.8 (± 2.2) % flame retardant based on ammonium salts and biocide.	[115]
Products with very high additive content	Wood-plastic composites	30–55% wood (flour, fibers, granulates ...)	30–70% virgin and regenerated plastic resins (PE, PP ...)	<20% including chemical additives (<10 wt%), lubricants (4–5 wt% for wood-PE or 1–2% for wood-PP), coupling agents (3 wt%), catalysts, foaming agents, antifungal biocides, dyes, colorants and UV resistance (1–3 wt%)	[116–119]
		30% flax shives	70% polyvinyl chloride (with additives)		

^a Confidential composition (nature and/or proportion).

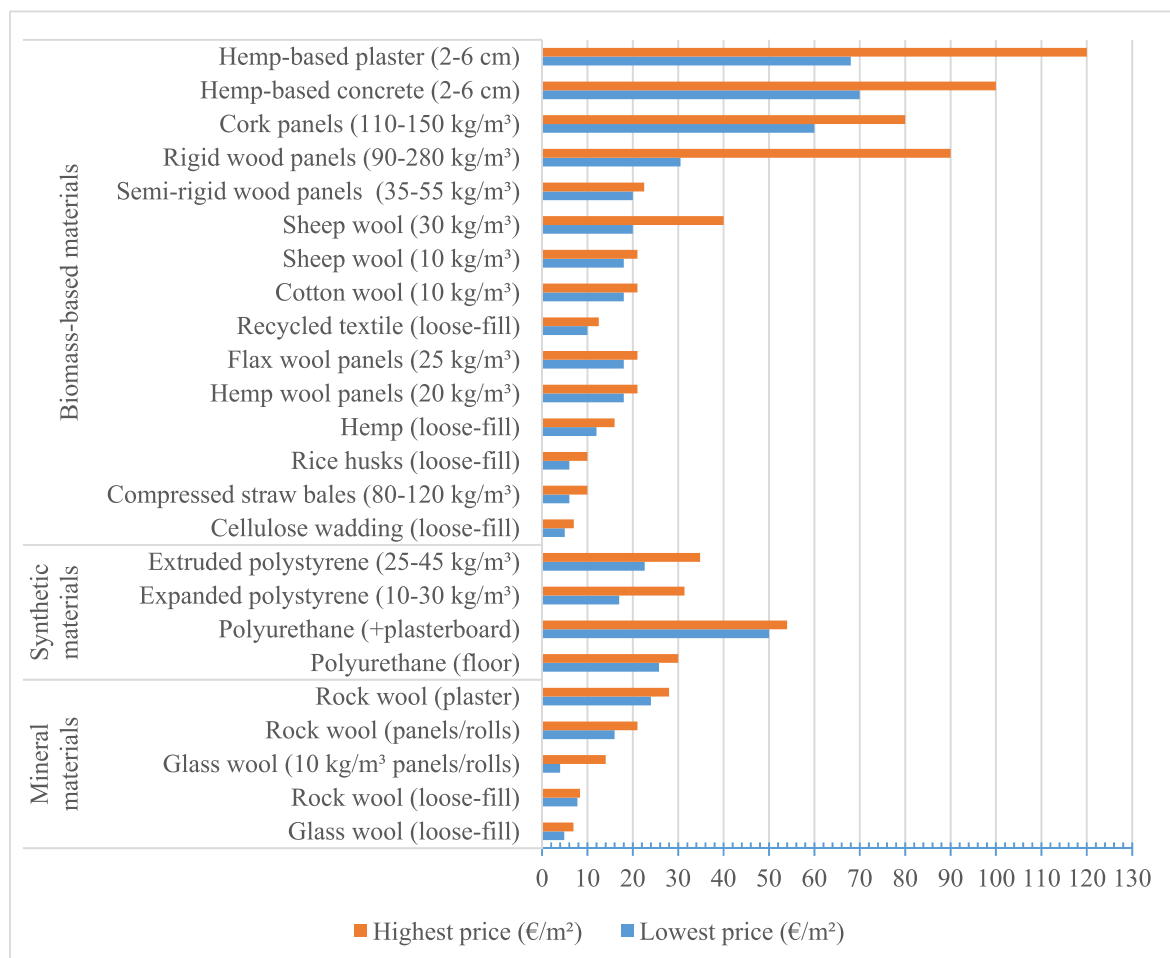
[123]. Different simulations translating the need for bio-based materials were carried out by varying the pace of three parameters; construction/rehabilitation, future market shares of bio-based materials and wood-frame construction (WFC). The retained scenario “Rehab ++, Bio-based ++ and WFC ++” is a combination of two scenarios to which

the assumption of a significant increase in the market share of WFC has been added [123]. This scenario is harmonized with the commitment and the determination of the French government via “France National Low Carbon Strategy” aiming to make the building sector carbon neutral by 2050.

Table 4

Volumes of bio-based building products manufactured and commercialized on the French territory.

Bio-based building material	Form in the building	Volume Commercialized in France (tons/year)	Year of reference	Current commercialized volumes in 2020 (tons/year)	Expected commercialized volumes in 2030 (tons/year)	Expected commercialized volumes in 2050 (tons/year)
Cellulose wadding	Loose-fill fibers	40,000 to 50,000 [58]	2016	70,000 to 100,000 [30] or 73,000 ^b (+10% AGR)	90,000 to 160,000 [30] or 120,000 ^b (+5% AGR)	182,160 [123]
Flax	Prefabricated panels					
Wood fibers	Flax/hemp panels	7200 [60]	2016	8500 ^b (+4% AGR)	12,000 ^b (+3.5% AGR)	17,077 [123]
	Soft and medium-density boards	40,000 [58]	2017	53,240 ^b (+10% AGR)	110,000 ^b (+7.5% AGR)	183,000 ^c [123]
	Hardboards	70,000 [58]	2017	93,170 ^b (+10% AGR)	192,000 ^b (+7.5% AGR)	327,000 ^c [123]
	Wood-plastic composites	15,000 [30]	2011	40,000 [30]	60,000 [30] or 65,000 ^b (+5% AGR)	107,000 ^b (+5% AGR)
Cereal straw	Straw bales	4600 [58]	2016	- (no AGR)	- (no AGR)	15,709 [123]
	Straw panels	4400 [60]	2012	- (no AGR)	- (no AGR)	-
Hemp	Hemp wool panels	2500 [58]	2017	2800 ^b (+4% AGR)	4000 ^b (+3.5% AGR)	30,739 [123]
	Loose fibers in bulk	3000 [58]	2017	3500 ^b (+4% AGR)	5000 ^b (+3.5% AGR)	20,081 [123]
	Hemp concrete	40,000 [58]	2017	- (no AGR)	- (no AGR)	-
Recycled Textiles	In bulk and rolls/panels	3500 [58]	2017	10,000 [60]	20,000 [123]	50,000 [123] (17,077 in loose-fill)
Sheep's wool	Rolls/soft boards	3000 to 4000 [60]	2012	4000 ^b (+4% AGR)	5800 ^b (+3.5% AGR)	5000 [123]
Cereal husks	In bulk or panels	4040 ^a [58,124]	2018	- (new market)	-	-
Cork	Granulated cork	1500 ^a [60] (cork is imported)	2012	2100 ^b (+10% AGR)	4300 ^b (+10% AGR)	25,047 [123]

^a Volume produced in France (without taking into consideration importation and exportation).^b Volume calculated based on Annual Growth Rate.^c Volume obtained based on the data provided by the TERRACREA project.**Fig. 3.** Market price (in €/m² excluding VAT) of mineral, synthetic and bio-based insulation materials in 2016 for R = 5 m² K/W.

Referring to the volumes, several key points have to be noted:

1. The sheep's wool insulating products are currently disappearing with time, linked to the difficulties related to the high price, poor quality of wool and the inexistence of a low-cost washing process in France. Owing to the market slowdown, the availability of sheep-based products for construction is capped at around 5000 tons by 2030 and 2050 [123].
2. The production volume of wheat straw panels is very low (<400 tons/year in 2012). This market is immature (products poorly characterized) since no recent values are provided and no reliable statistics nor baseline data exist.
3. The rice husk is a novel industry that is still under development. The market for loose-fill rice husk or insulating panels is around 4000 tons in 2020. The future market of these products in France is uncertain. In the literature, no annual growth rate is envisaged nor is the evolution of the production by 2050. Besides, no EPDs exist for these materials and the composition is still unclear and/or unknown for confidentiality reasons.
4. The tonnage of flax materials within the building is assumed to remain unaffected until 2050 owing to the strong demand for flax in the textile sector. Thus, the future availability of co-products will persist at the same level as today [123].
5. The quantities of recycled textile and cellulose wadding are likely to increase significantly in the future due to the wastes associated with fast fashion (cheap and trendy clothes) and newspapers.
6. Cork importation is expected to decrease in the future owing to the revival of this sector by replanting or carrying on maintenance of abandoned or badly managed cultivation areas. In the best case, the French-origin cork may reach 25,000 tons/year by 2050 in buildings [123].

2.6. Selling price on the market

Many studies have reported that bio-based materials cost more than traditional and synthetic building materials [5,125]. In this review, the prices of bio-based materials and their conventional competitors in 2016 are presented in Fig. 3. The price differences are mainly elucidated by the product's market shares. The low cost of mineral insulating materials is associated with their market dominance (50% of the insulation market). Despite their relatively considerable prices, the petro-sourced materials have a high market share (40% of the insulation market) associated with the small thickness needed to ensure high thermal resistance [77]. The low market share of eco-materials (10% of the insulation market) is interrelated to their high cost. Nevertheless, this percentage is set to increase and prices are to be falling thanks to the RE 2020 that targets the realization of positive energy buildings and the reduction of the carbon footprint of new dwellings. The insulation of the latter buildings imposes a higher minimum thermal resistance per insulated area than Low-Energy Buildings. The attics must be insulated with a material possessing $R > 10 \text{ m}^2 \text{ K/W}$ whereas walls/floors should be insulated with a material having $R > 5 \text{ m}^2 \text{ K/W}$. Therefore, to meet the requirements of the new regulation, 3BMs are detected to be highly competitive in terms of reasonably low-cost products associated with high performance [81].

2.7. Lifespan and durability

In general, the lifespan of 3BMs fluctuates between 10 and 50 years. The WPCs applied as outdoor decking have a short useful life of 10–20 years. However, sheep's wool dedicated to interior insulation rolls has a useful life of 20–30 years as being less stable, in terms of mechanical properties, than the remaining natural fibers having long lifespans between 40 and 50 years. Besides, the incentive nature of the implemented energy transition policies has a significant impact on the service life of the wall insulation, but a low impact on the service life of the roofs.

Hence, the useful life for the insulation of roofs and walls is 20–25 years in the framework of incentive energy transition policies. A differentiated useful life of 40–50 years for wall insulation is noticed in case of low or lack of incentive public policies [30].

The durability of indoor and outdoor 3BMs is defined as the ability of a material to resist the long-term damaging caused by itself or by the surrounding environment. This parameter is affected by several factors, such as the nature of the raw material (microstructure); the quality of the material (hygroscopic); the installation technique; rodents and the in-service conditions (temperature and relative humidity or moisture content) [126,127]. The pH is an important factor affecting the durability of biomaterials since it is related to microbial proliferation [5]. An inappropriate or poor implementation technique (blown-in), in which the material is imperfectly installed in place (with air gaps leftovers) or subjected to high loads, may lead to dimensional instability and the deterioration of the material's thickness. Consequently, the thermal properties are changed, thus the durability of the material is negatively affected by air infiltration. For instance, blown-in flax wool and cellulose wadding tend to settle over time. The greater the settlement, the lower the thermal resistance of the insulation [53]. To hamper the settling, it is advocated to enhance the thickness of cellulose wadding by 10% after filling the cavities [128]. Moreover, rodents are one of the main threats to deteriorating insulated spaces. These animals are biomass-degrading agents, building their nests in the insulation after ripping it up into tiny shreds, thus leading to the compaction and the elimination of the insulation system. Furthermore, the temperature rise will lead to the growth of insects, more particularly termites and beetles. Therefore, the organic structure (nutrient source) of the dry or low-moisture content biomass-based material becomes prone to insect attack. Owing to climate change, the hazards related to these insects are expected to rise soon [126]. Finally, moisture is noticed to strongly impact the properties of bio-based construction materials. When these latter are exposed to weathering (ultra-violet radiation) wetting and flooding (exterior application) or subjected to potential water condensation (interior application) due to high relative humidity (>95%), the mechanical performance is degraded. These include the reduction in hardness and strength along with shrinking and swelling due to the dimensional change (deformation) of lignocellulose thus resulting in material cracking [5]. This will result in the modification of the thermal and acoustic properties of the material. In addition, a high water concentration impacts (wet spraying) the serviceability and durability of the building materials since it stimulates the development of microorganisms (bacteria, mold, fungi ...) [129,130]. The latter will give rise to biological degradation (noteworthy loss in lignocellulose mass and strength) and thus the material's functional performance and optical appearance are impacted [131,132]. The susceptible undesirable degradations cannot be entirely prohibited but may only be decelerated by biocides and water repellents along with the over-ventilation of the wetted spaces to speed up the drying process. Therefore, biomaterials are quite far from achieving adequate levels from a technical perspective [5].

2.8. Existing end-of-life scenarios in LCAs and EPDs

When the insulation product is noticed to have lost its initial intended thermal/acoustic properties and no longer serves its original function, it has reached its EoL. As becoming waste, the product needs to be collected from the building before discarding [133]. In France, the waste definition is relatively harmonized with the European one. The European Waste Framework Directive 2008/98/EC along with the EC (Law 75–633 of July 15, 1975) and the French decree 2002–540 of April 18, 2002, strongly define the waste as “any residue from a production process, from processing or use, any substance, material, product or, more generally, any movable property that is abandoned or is intended to be abandoned by its holder” [134,135]. To go beyond the linear economy, the legislations have encouraged the transition towards a

circular economy aiming, in order of priority of waste hierarchy, at the preparing for reuse (secondary product), the recycling (reprocessing to fulfill its original function or other purposes) or the recovery (conversion of waste into materials, fuels, heat and power) [136]. The French EC has also enacted the polluter-pays principle for waste reduction [137].

The management of bio-based building materials at EoL is

exclusively important as these materials usually end up in the 230 landfilling sites or the 126 incineration plants existing over the French territory, thus impacting negatively the environment and endangering human health [138]. In France, the target consisting of reusing and recycling 70% of the building and public work's wastes up to 2020 is reached [8]. However, this fraction consists mainly of inert wastes

Table 5

Existing recovery scenarios of bio-based insulation wastes.

Bio-based building material	Dismantling technique	Exiting EoL scenarios in EPDs and LCAs	Scenario description	Reference
Hempcrete	Demolition or deconstruction of walls using an excavator	Landfilling	In inert waste storage facilities	[142]
		Recycling	Crushing, and spreading as acid soils enrichment/amendment (composting)	[143]
			Crushing and sieving into coarse aggregates (>2 mm) as a substitute for fresh hemp shives for new hempcrete production to be used in building	[94]
Wood-based concrete block			Fine aggregates used as filler in asphalt mixes and as a substitute for sand in mortars	[144,145]
		Backfilling	Coarse aggregates for pipe excavations construction of parking areas or streets	[146,147]
		Landfilling (30%)	In inert waste's storage facility (30 km): 15% wood degradation (15% of biogenic carbon released in the form of CH ₄ (50%) and CO ₂ (50%))	[148,149]
Wood-plastic composites	Manual	Material recovery (70%)	Crushing and screening for backfilling in road engineering techniques, as alternatives to natural aggregates	[148]
		Recycling	Crushing and pursuing CO ₂ mineral carbonation (0.049 kg CO ₂ absorbed/kg concrete)	[95,145, 148]
		Recycling	Reincorporation of up to 30% of good product quality WPC's wastes into new production (one cycle)	[27,150, 151]
Straw bales (without additives)	Selective deconstruction of buildings dismantling of walls	Energy recovery	Incineration predominant	[150]
		Reuse of bulk straw	Reconditioning straw into bales is of almost no technical or economic interest	
		Recycling (recommended by PRSC)	For agricultural purposes: compost, organic soil amendment, mulch for market gardening, yards and parks.	[98]
Straw/renders	Manual stitching	Energy recovery (recommended by PRSC)	Incineration in boilers (or incineration plants) for its conversion into fuel and energy (significant low heating value of 16.51 MJ/kg)	[98]
			Anaerobic digestion for biogas production and digestate composting	[152]
			In non-hazardous waste storage facility (1%)	[98]
Straw panels	Manual	Landfilling	In non-hazardous waste storage facility	
		Landfilling	Composting 80% if deprived of additives	
		Agronomic recovery	In non-hazardous waste storage facility	
Rice husk	Manual or aspiration	Landfilling	In non-hazardous waste storage facility	
		Landfilling	Reprocessed for the production of low-grade products (no real example)	[153]
		Recycling	Incineration (environmental impact)	[154,155]
Flax/hemp panels	Manual	Energy recovery	Low heating value of 18 MJ/kg	
			Predominant waste disposal	[154,155]
			Reuse about three times if fibers length is adequate and not polluted	[156]
Flax wool		Landfilling	For new material production or reprocessed for the manufacturing of low-value products (no actual example and no detailed information)	[153]
			Stabilizing into the asphalt mixture	[156]
			Release of all the biogenic CO ₂	[157]
Cellulose wadding	Separately recovered by aspiration	Incineration with energy recovery (53%)	The low heating value of 11.83 MJ/kg at 5% humidity	
		Landfilling (47%)	1.5% degradation:CH ₄ (50%) and CO ₂ (50%)	
			70% of landfills are equipped for CH ₄ flaring (30% CH ₄ emission)	
Hemp-based panels	Manual	Landfilling	Transported for around 30 km to a non-hazardous storage facility	[158–160]
			Release of 90% of CO ₂ and 9% of CH ₄	
			Dominant treatment (100 km)	
Recycled textile	Manual or aspiration	Landfilling	Hazardous chemicals leaching and landfill gases release	[161]
		Reuse	Potential route	[162]
		Energy recovery	Not well explored/documentated	
Wood-based products	Demolition or selective deconstruction	Incineration: toxic fumes and gases (dioxins, toxins or furans, CO ₂ and CO)	Gasification: under development (CO/H ₂)	
			Occupy huge land space.	[144]
			CH ₄ emissions	
Cork	Manual or aspiration	Leachates (additives, coating, varnish, glue) infiltration into soil and water contamination	Incineration is favored for treated wastes with metals or organochlorinated compounds	[164,165]
		Energy recovery	Crushed and recycled for animal bedding, composting or particleboards production	[166,167]
		Material recovery (if untreated)	Composting, manufacturing of new insulating panels, concrete and lightweight coatings	[158,164]
Sheep's wool	Effective separation (dismantling)	Recyclable (loose/panels)	Incineration favored in the presence of polyurethane glue	[164]
		Energy recovery	No VOCs nor toxic gases emissions	
		Reuse, recycling or landfilling	Compost production (if plastics separated)	[33,158]

driving from public work. New targets are to be set for the upcoming period, more precisely for the material/energy recovery of non-dangerous and non-inert building wastes including insulation wastes. Despite the little information provided on the existence of some recovery channels, the recycling rate of the arising wastes is still extremely low and no recycling process has been developed, except for bio-based concrete [139]. Although the producer's declarations advertise their bio-based insulating materials as 100% recyclable, several obstacles hinder their recyclability [140,141] predominantly the limited quantity of waste and the absence of proper dismantling, organized sorting, and collection methods at the source. Table 5 summarizes the existing recovery scenarios for the management of bio-insulation wastes after building renovation or deconstruction.

3. Potential recovery routes

Today in France, bio-based building materials are becoming a reality owing to their significant market share that is dependent on their commercialized volume on the French territory. A noteworthy deposit of wastes is estimated by 2030 and 2050, hence the awareness towards forecasting specific actions to recover this volume of materials, which is theoretically recoverable [30]. Coupling selective deconstruction and sorting is primordial [168]. Therefore, in compliance with the waste treatment hierarchy, reuse, recycling and energy recovery have to be examined extensively as depicted in Fig. 4, before landfilling. Consequently, the ETAGG has set different targets intended for minimizing landfilling and maximizing material and energy recovery. The main goals are the material recovery of 65% of the non-inert and non-hazardous wastes by 2025, the energy recovery of all the non-recyclable wastes resulting from a sorting facility starting from 2015, and cutting by half the quantities of landfilled non-hazardous and non-inert wastes by 2025 [79].

3.1. Hurdles impeding the reuse

Among the waste management practices, reuse is explored as the best waste treatment operation allowing a secondary utilization of waste [169,170]. Several materials such as pallets, wood from formworks, doors wood frames, beams, slabs, tiles, concrete, bricks, ceramic sanitary equipment can be reused [147,171]. Nevertheless, no studies have explored the possibility of reusing bio-based building wastes as few buildings integrating these materials are yet demolished or renovated. When selective deconstruction is executed, the wastes may be potentially reused, but this option is marginal at this time as their thermal properties may be altered over time. Another reason is the lack of traceability and lack of information reliability (manufacturer details and information on the production process, confidential formulation, ...), hence leading to heterogeneous supply and purchaser's doubts about the quality of the secondary product due to lack of material standards [172].

Besides, this technique is advocated and only feasible if the fibers are not damaged nor contaminated by impurities such as dust, plaster or earth. Yet, this latter condition is rarely met due to dust accumulation, particularly when cellulose wadding is removed by aspiration. Moreover, the presence of pigments, additives and plastics along with the unbearable separation of these latter from the lignocellulosic matrix can lead to the failure in the current guidelines for reuse [150]. Plus, the use of recycled plastics in the manufacture of the WPCs can significantly reduce the number of cycles of its reuse [97]. The reuse option is poorly documented in the literature and has to be examined genuinely in the future since it leads to economic and environmental benefits associated with the manufacturing of new products [173].

3.2. Hurdles impeding the recycling

Considered an essential strategy in the circular economy, recycling is depicted as an environmentally effective practice aiming at the minimization of the exploitation of natural resources and landfills [169,174]. This practice may be achieved via two techniques: off-site recycling in treatment plants and on-site recycling. When coupled to on-site sorting, this latter technique is recognized to be the most efficient technique for waste treatment in terms of environmental aspects. The application of this waste management technique ensures a reduction in energy consumption (depending on the material type) along with considerable economic benefits, particularly linked to the avoidance of the construction of new landfills [175,176]. When a substitution ratio is estimated, the performance of the recycled materials must be measured by testing their intended properties [176].

Despite being favored, this option does not seem appropriate for all insulation products because of multiple barriers. The first problem is the mixing of 3BMs with hazardous wastes during conventional demolition [140]. Besides, this latter technique hampers the differentiation of building materials and hence decreases the potential for salvaging valuable products [141]. The second is the limited quantity of waste generated, below the threshold of 10,000 tons required for developing an economically viable recycling route [30,133]. The third is the composition of the bio-materials such as the additives incorporated and the thermoplastic resins bonded. Assuming that the formulation does not evolve with time and that the climate conditions do not alter the product characteristics, the sorting, separation of components and recycling are costly and challenging. Indeed, owing to the presence of different types of resins and fibers along with variable biomass grain size distributions, specific sorting tools (molecular, fluorescence or near-infrared sorting techniques) will be required, leading to additional costs and complexity [97]. Adding to these, the presence of plastic binders and additives rules out the possibility of agronomic/material recovery [153]. The composting of adjuvanted bio-based materials in the presence of oxygen and microorganisms [177] is not permitted in the EU. The water-soluble additives may leach hence posing adverse

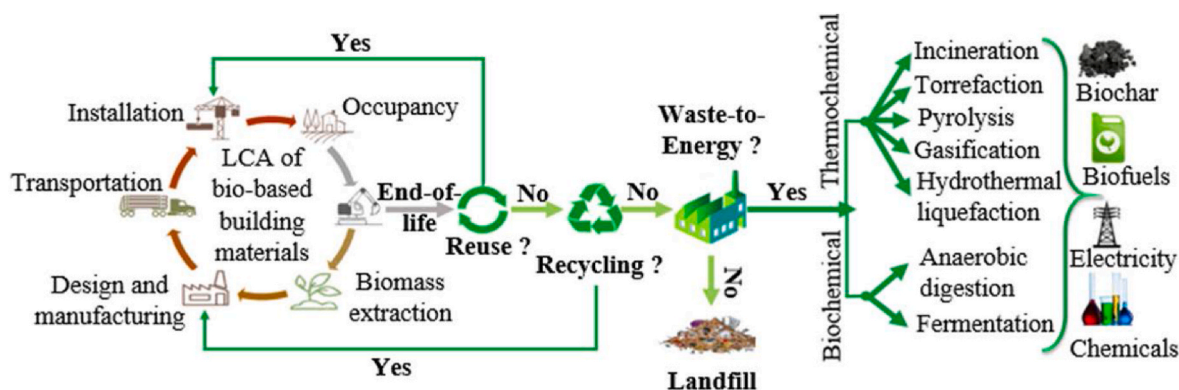


Fig. 4. Bio-based building materials valorization scenarios at end-of-life, in compliance with waste treatment hierarchy.

environmental concerns. Further, this process emits toxic gases including VOCs and GHGs into the atmosphere that are not valorized nor purified [178].

Above and beyond, the recyclability of 3BMs is limited by several restrictions such as the managerial, legislative and economic hurdles [173,179]. These obstacles include the lack of public incentives and the lack of contractor culture and awareness about the environmental benefits of recycling [172], the budget deficiency for discarded materials' treatment in construction plans, the nonexistence of eco-viable recycling routes and the low dumpsters fees [180]. In the building industry, the use of the recovered materials is influenced by marketing problems including lack of standards and regulations for the management of insulation wastes [170,172,180], absence of technical data about the product [170,172], low market demand [170,180], high price compared to new materials [179] and scarce/unsteady supply of insulation wastes [172]. A. C. Schmidt et al. [153] have performed LCAs for flax wool and cellulose wadding. According to this study, the wastes are collected and directed towards a recycling unit where they may be reprocessed into low-grade products without specifying a real example.

To improve the recycling rates of 3BMs at EoL, more work has to be performed on the design and construction stages. The aim is to minimize toxic and hazardous additives along with the layering and secondary finishes (glues, gypsum, ...) for improving the product quality and durability [173]. Besides, selective deconstruction has to be favored when compared to demolition. The systematic disassembling of building material improves the prospect for closing material loops, thus making the best use of building materials and components [175]. Nevertheless, this EoL practice is not widely implemented and composting is a real issue [170]. Therefore, a more efficient and better organized on-site sorting of the waste is needed for easier and better recycling [168].

3.3. Hurdles impeding landfilling

Although being reported in most EPDs and LCAs, landfilling is considered as the worst scenario and the least to be selected for the management of wastes. First, the storage facilities occupy a huge land space and are frequently not equipped with a landfill gas recovery system [181]. The huge amount of wastes buried contribute to severe environmental burdens including the CH₄ emissions into the environment, hence accentuating global warming. Moreover, the environmental impacts are associated with the leachates infiltration into the soil and the contamination of the underground water. These leachates originate from the surface additives, chemicals, coatings, varnishes and glues used for stabilizing the insulation material and lengthening its durability [144]. Biocides such as 2-octyl-2H-isothiazol-3-one (OIT) [182] are identified to have a low solubility in water, hence prone to excessive leaching [183] when the material gets in contact with rainwater or ultra-violet light [184], hence posing ecotoxicological risks. In France, ever-improving waste management plans and efforts are currently made by manufacturers for the discovery of alternative recovery routes to landfilling for bio-based insulation wastes [161].

3.4. Waste-to-energy: a promising route

Biomass-based materials deriving from available lignocellulosic wastes (wood and agricultural wastes) consists predominantly of lignin and carbohydrates comprising hemicellulose and cellulose [185,186]. Recently in the literature, the Waste-to-Energy (WTE) processes are rewarded with special attention for the treatment of non-recyclable waste. One of the WTE practices already adopted in EPDs for the management of 3BMs waste is incineration. Several obstacles hinder its implementation, hence the orientation to eco-friendly processes.

3.4.1. Barriers hampering incineration

At present, incineration remains the most mature WTE technology applied worldwide. In Europe, 455 incineration plants were operating in

2012 [187], out of which more than 100 incinerators are widely spread over the French territory [188]. Incineration is the combustion of materials at elevated temperatures in the presence of excess oxygen. This treatment option reduces the waste volumes while being unsustainable because of its associated environmental impacts (nitrogen or sulfur oxides, dioxins, toxins, dust, ...). Besides, 20–25% of the feedstock is noncombustible and hence not burnt, goes out as ash including heavy metals and poisons, hence damaging the environment. Despite the presence of European regulations limiting the emissions [188,189], pollution cannot be avoided because of no "zero thresholds". Moreover, the ash fraction is transformed via several reactions into complexes leading to bed agglomeration in incinerators, corrosion, fouling, slagging and deposition [190]. Therefore, this energy recovery technique must be combined with combustion gas treatment (dusting, neutralization, trapping of heavy metals) to avoid pollution transfer to the surrounding, thus resulting in additional costs. Although using the recovered energy as an alternative to fossil fuels [181], this method does not lead to the formation of value-added products, thus the focus is driven towards more economical and environmentally friendly WTE conversion techniques.

3.4.2. Prospective eco-friendly WTE technologies

The efficient and ecological WTE can be performed via thermochemical or biochemical technologies. The former technology is rapid and involves the thermal decomposition of all plant organic components (carbohydrates, lipids, proteins and lignin) into small molecules, in the presence or absence of catalysts, at atmospheric or high pressure. However, the latter technology involves the use of various microorganisms (bacteria, yeast, fungi, ...) under distinctive operation conditions for the sole conversion of biodegradable sugar wastes to bioenergy. Both technologies may be used to produce biofuels, added-value products, or platform chemicals. Thermochemical conversion routes include mainly torrefaction, pyrolysis, gasification and hydrothermal liquefaction, while biochemical technologies consist of anaerobic digestion and fermentation. Table 6 describes these WTE conversion processes, their main conditions, key products, characteristics, their application field along with their possible coupling to other processes. All these technologies present some environmental bottlenecks linked to the waste composition and the energy recovery rate [188].

Owing to their environmental benefits, the application of pyrolysis and gasification at an industrial scale is today emerging in developing countries. Over than 100 gasification facilities have been functioning; most of them are situated in Japan with a limited number in Europe. In Finland, some gasification plants are already operating for the treatment of organic municipal solid wastes [188]. In Italy, around 36 small-scale gasification plants are geographically distributed over the territory and operating for the generation of both heat and power from woody wastes and pellets [191]. In France, the research and development activities are currently focusing on the technical, economic and environmental feasibility of industrial pyrolysis and gasification as these processes can be often energy and cost-intensive.

3.4.3. Energy recovery and potential CO₂ saving

Landfilling is currently reported as the waste management practice to be adopted for future 3BMs wastes at EoL in 2050. In EPDs, around 15% of landfilled wastes is estimated to be degraded into CO₂ (50%) and CH₄ (50%) whereas 85% of the carbon is sequestered hence occupying a huge area. This biogenic CO₂ fraction is estimated to be captured by plants, while this is not the case for methane fraction. Although both gases have greenhouse effects, the CH₄ release contributes 25 times more to global warming than CO₂. Displacing waste landfills and avoiding their free associated CH₄ emissions might be achieved by the development of an alternative scenario consisting of improving the energy recovery throughout WTE technologies [217]. The significant lower heating value (LHV) of the 3BMs wastes allows energy recovery while preserving the burning of an equivalent amount of fossil fuels for

Table 6

The different eco-friendly waste-to-energy conversion pathways.

Conversion route		Conditions	Products	Products characteristics	Application	Combination	
Thermochemical	Torrefaction	Slow heating (<50 °C/ min) Slightly oxidizing or inert atmosphere Low T: 200–300 °C	Charcoal (brittle and hydrophobic) [192]	High C content Low O and H contents High energy density [193]	Energy production (gasifiers, combustion units and power plants)	Followed by pyrolysis or fermentation [194]	
	Pyrolysis	Quick/slow heating Dry materials High T: 400–600 °C No oxygen Pressure = 1 atm	Biochar	Influenced by feedstock composition and operating parameters (temperature, residence time and heating rate) [193]	Activated carbons CO ₂ sequestration materials Sorbents Catalysts for syngas cleaning Fuel cells Structuring element for the soil [195] Liquid fuel [196] (jet fuel, diesel, gasoline) after upgrading [197] for transport sector Internally recycled Reused as fluidizing gas or energy [198]	Pretreatment: Torrefaction Followed by gasification	
			Pyrolysis oil				
			Gas phase (CH ₄ , H ₂ , CO ₂ , CO)				
	Gasification	Oxidizing/gasifying agent (steam, CO ₂ , O ₂ or air) Pressure = 1 atm T: 600–1000 °C Short residence time (3–4 s) [199]	Syngas CO/H ₂ (including CH ₄ and poisonous molecules: COS, H ₂ S, HCl ...) [200] Cleanup needed [201]	High energy content High H/C ratio Low O content	Generating heat and power (boilers, engines, fuel cells, turbines) Syngas conversion to liquid fuel, commodity chemicals or methane (energy) via downstream processes (Fischer–Tropsch synthesis, Water-Gas Shift Reaction, methanation, ...) [200] Value-added chemicals (aromatics, phenols, ketones, esters, aldehydes, alcohols, acids, ...) for industrial applications [204,205] Liquid fuel (diesel, gasoline, ...) [206] Fertilizer Solid fuel Catalyst	Preceded by pyrolysis for maximum syngas yield	
	Hydrothermal liquefaction	Wet biomass High T: 300–400 °C) Pressure = 5–20 MPa) [202] Liquid/supercritical water or solvents Exposure time (0.2–1.0 h) [203]	Oily phase	High bio-oil quality High heating value High oil yield (20 and 60 wt%) [202] Quality and yield improved by catalysts		Combined with fermentation process	
			Solid phase				
Biochemical	Anaerobic digestion	High-moisture content feedstock (high sugar and volatile matter, low lignin and ash) Oxygen-free atmosphere	Gas phase (CO ₂) Biogas [207]: CH ₄ (50–70 mol%) CO ₂ (30–40 mol%) Pollutants (VOCs, O ₂ , chlorine, steam, ammonia and H ₂ S [208,209])	Biogas yield depends on biomass	Heat and/or electricity generation [210] after biogas cleaning [211] Biomethane injection into the gas grid or compression for use as transportation biofuel [212, 213] after biogas upgrading (minimizing impurities and CO ₂) [208,214,215] Biofertilizer High-grade liquid fuel (bioethanol) [1] Cattle-feed Fuel for boilers or gasification	Preceded by delignification and saccharification [216] Followed by gasification or incineration of solid residue	
	Fermentation	High sugar-based biomass Yeast presence Anaerobic conditions Regulated pH/T	Digestate [207] Dilute solution of alcohol CO ₂ Solid residue	Low biofuel yield depending on biomass sugar content)			

heat/electricity production. Moreover, the energy production can be reinserted into the system for the manufacturing of new products. Therefore, this scenario reduces the consumption of fossil fuels for energy and reduces the waste volume by converting all the carbon into CO₂ that will be subsequently picked up by plants.

In this study, the environmental impacts of landfilling and the benefits of implementing energy recovery scenarios were compared. Since waste to energy routes have different energy carriers and by-products yields associated with different efficiencies, Table 7 addresses the maximum energy recovery potential with the transformation of total carbon content into CO₂. For landfilling, the Global Warming Potential (GWP) of the released methane resulting from the future degradation of the insulation wastes was estimated. The future deposits were assessed based on the commercialized quantities in France and their service life,

hence becoming wastes in 2050. The GWP values were extracted from EPDs and LCA analysis. As CO₂ will be assimilated by plants, only methane's GWP was calculated in kilograms of CO₂ equivalent per Functional Unit (kg_{CO₂eq}/FU) of material for a reference life expectancy of 50 years. This latter corresponds to the period after which the manufacturer considers that, under normal use, the product or equipment no longer provides functionality and has reached its EoL. The FU is defined as the thermal insulation of 1 m² of a roof or wall by the bio-based product ensuring a thermal resistance of 5 m² K/W. For the energy recovery, the LHV values were extracted from the literature in GJ/ton. These values are then converted to toe based on 1 toe equal to 41,868 MJ. The resulting values are then multiplied by the emission factor of oil (3.07 t_{CO₂eq}/toe) [218].

Based on densities and the quantities of insulation products, the total

Table 7

Environmental impacts of landfilling and the benefits of energy recovery routes.

Bio-based building materials	Amount of wastes in 2050 (tons BBMs)	Density (kg/m ³)	Volume (m ³)	Landfilling				Energy recovery			Total CO ₂ saved (tCO _{2eq} /ton 3BMs)	Total CO ₂ saved (tCO _{2eq})
				Landfilling waste amount (kg/FU)	GWP at EoL (kg CO ₂ eq/FU)	CH ₄ GWP (kg CO ₂ eq/FU)	CH ₄ emission (tCO _{2eq} /ton 3BMs)	LHV (GJ/ton 3BMs)	LHV (toe/ton 3BMs)	CO ₂ saved (tCO _{2eq} /ton 3BMs)		
Mixed fibers (cotton/hemp/flax)	7200	30	240,000	3.0	4.8	2.3	0.8	17.0	0.4	1.2	2.0	14536.6
Cellulose wadding	50,000	30	1,666,667	4.7	5.7	2.7	0.6	12.4	0.3	0.9	1.5	74583.5
Hemp wool	2500	30	83,333	6.0	7.0	3.3	0.6	17.0	0.4	1.2	1.8	4508.6
Expanded cork	1500	185	8108	37.0	36.1	17.4	0.5	16.5	0.4	1.2	1.7	2518.4
Straw bales	4600	100	46,000	36.6	32.8	15.8	0.4	17.7	0.4	1.3	1.7	7932.8
Recycled textile bulk	1000	13	75,188	2.0	0.0	0.0	0.0	17.0	0.4	1.2	1.3	1256.9
Recycled textile rolls	2500	20	125,000	2.0	2.9	1.4	0.7	17.0	0.4	1.2	1.9	4835.1
Wood soft panels	40,000	40	1,000,000	8.0	0.2	0.1	0.0	18.5	0.4	1.4	1.4	54741.8
Wood rigid panels	35,000	130	269,231	13.0	1.4	0.7	0.1	18.7	0.4	1.4	1.4	49709.1
	35,000	150	233,333	14.5	35.4	17.0	1.2	18.7	0.4	1.4	2.5	88972.6
Flax wool	2000	30	66,667	6.0	7.0	3.3	0.6	17.0	0.4	1.2	1.8	3606.9
Sheep wool	4000	14	296,296	11.5	4.9	2.4	0.2	16.0	0.4	1.2	1.4	5515.6
Total	185,300		4,109,823	144.3	138.1	66.4						312717.8

volume of the products at EoL is 4.11 million m³. This volume is roughly equivalent to that of Montparnasse tower; a 59-floor building having a length of 209 m. Besides the massive volume required, the emissions of CH₄ from landfills storing all the insulation wastes generate 85,000 tCO₂ based on an average emission of 0.46 tCO_{2eq}/ton of waste.

The WTE routes could provide land savings and the minimization of CH₄ greenhouse effects, hence preserving the combustion of around 0.4 toe/ton of waste burned. As a result, 1.24 tCO_{2eq} are saved per ton of waste. Therefore, energy recovery of 3BMs waste allows conserving 75,000 tons of fossil fuels and saving the climate from the harmful effects of methane. This latter is substituted by biogenic CO₂ emissions needed for plants growth. Finally, 1 ton of waste is estimated to save 1.7 tCO_{2eq}, hence 315,000 tCO_{2eq} are saved by the conversion of 185,300 tons of wastes by 2050. In France, the estimated costs of the disposal of non-hazardous non-inert wastes in non-hazardous storage facilities (landfills) range between €45 and €76 per ton of waste [219]. By taking an average cost of €60 per ton, 11.1 million euros per year could be saved when avoiding landfilling. In addition, the average price of crude oil is \$50/bbl (€43.27/bbl or €1038.5/ton of crude oil) [220], hence 77.9 million euros per year could be saved. Therefore, energy recovery has the potential of saving 89 million euros per year that could be redirected to the implementation of WTE facilities.

3.4.4. Selection of the relevant waste-to-energy route

For a developing country, the selection of the most relevant and suitable WTE technology is dependent on the performance of the recovery system that in turn relies considerably on the geographic aspects [188] including the types of waste (organic/inorganic), the investment and operating costs, the complexities and efficiencies of the process [221]. Prior to developing a biorefinery in a particular country, the decision-making criteria recommended are as follows:

- The merits and boundaries of each conversion process [222,223].
- Technical and economic feasibility of each technology for a specific type of waste and region [222,223].
- The composition of the waste stream and its biochemical characterization [223,224].

- The generation rate for each waste type [225].
- The energy content of each waste type [223].
- The LCA of the biorefinery technology including its technical, financial and environmental assessment [222,226].

The merits and demerits along with the technical (complexity, labor skill level, daily power generation, geographical location and efficiency) and economical (capital and operational costs) values of each waste-to-energy technology are extensively defined in the literature and reviewed by Nizami et al. [222] and Ouda et al. [223]. These studies have reported that AD of organic wastes is the cheapest technology with the lowest annual capital cost (US \$0.1–0.14) and net operational cost per ton of waste. The daily power generation of AD is extremely low (0.015–0.02 MW/ton of waste over the lifespan of the biomethanation) while the process efficiency (25–30%) is comparable with the other processes. The complexity of this technology and the labor skill requirements are low and hence can be implemented in rural zones. On the other hand, Ouda et al. [223] have found that pyrolysis and gasification are complex processes requiring intermediate to very high labor skill levels. Pyrolysis has a lower investment (US \$17–25) and operating costs (US \$2–3) as compared to gasification investment (US \$19.5–30) and operating costs (US \$2.5–4). The higher process efficiency (32%) and daily power generation (0.04–0.045 MW/ton of waste) are the main advantages of gasification compared to pyrolysis (17% and 0.01–0.014 MW/ton of waste). Both technologies are suitable to be implemented in urban areas.

The type of waste is an important criterion to be considered. This factor is essential since the integrated inorganic additives may be able to modify the valorization route for the products along while being toxic to human health and the environment. The biochemical technologies are restricted to organic wastes while thermochemical processes can convert organic and inorganic wastes [223]. The binders are not considered since they are inert or plastic compounds, with little or no risk of degradation in nature. They can be separated from the products prior to biochemical conversion or decomposed through thermochemical conversion processes.

Besides, the composition of the feedstock is the paramount factor for

directing the waste towards a specific biorefinery technology. For instance, pyrolysis and gasification are favored for low moisture content (<40%) [185,227,228], whereas direct liquefaction and biochemical conversion routes are favored for high moisture content biomass (60–80%) [227,229]. Moreover, thermochemical and biochemical routes are favored for cellulosic and hemicellulosic biomass, as the degradation of these compounds leads to high volatile products [230], and consequently high bio-oil and bioethanol yields. Furthermore, thermochemical technologies are privileged for lignocellulosic biomass as lignin acts as a barrier to fermentation and anaerobic digestion [231]. Therefore, the biochemical technologies are favored for high carbohydrate (>65%), low lignin (<10%), low ash (<1%) and high nitrogen contents (>0.2%) biomass [232].

The energy content of the waste and its generation rate are significant features suggested to be analyzed for choosing the suitable WTE technology. Biochemical technologies are favored for low energy content feedstock (food, untreated papers, grass) and are not attractive at an industrial scale owing to space requirements. Nevertheless, thermochemical processes are fostered for high and low energy content substrates (wood, textiles, treated papers, plastics, ...) and are suitable for significant waste volume reduction at large-scale [223]. Several studies have investigated the emerging use of untreated newspapers for the production of bioethanol throughout the fermentation process to minimize the load on landfills [1,233].

To date, the treatment of insulation wastes incorporating chemical additives is limited and is rather a challenge. Biorefinery technologies could be attractive due to the high organic content of panels, hence these latter are suitable feedstock for the production of second-generation biofuels, chemicals, fertilizers, heat and electricity [185]. If developed, waste biorefineries could provide the saving of natural resources, soil and land, the reduction of GHGs emissions, the saving of landfill costs and the creation of new businesses [222].

According to the aforementioned information, thermochemical conversion technologies are favored for chemically-treated and lignocellulosic biomass-based insulation materials as having low moisture content and high energy content. However, the decision to choose the optimum WTE scenarios for biomass-based insulation materials needs additional deep financial, social, technical and environmental analysis using LCA tools.

Recently, more attention has been paid to the energy recovery from insulation wastes. The pyrolysis [234], steam [234] and CO₂ gasification [235] of treated recycled papers were examined owing to the toxicity of the combustion and disposal of boric acid [236]. In addition, numerous investigations are conducted on the production of activated charcoal from hemp pyrolysis and gasification [237]. Yasin et al. [163] have studied the gasification of textiles treated with FRs. They have concluded that gasification is favored compared to incineration as it improves the syngas composition while avoiding the risk of hazardous compounds' formation due to the oxygen-deficient atmosphere. Hossain and Poon [165] have evaluated WTE on wood-based panels and have concluded that this technique is the preferable option for saving GHGs emissions and non-renewable energy consumption.

3.5. The integrated waste biorefinery concept

To promote a circular bioeconomy, the integrated waste biorefineries concept was developed in 2003 as a relevant answer to the existing waste disposal practices [238]. This new concept involves the integration of several biochemical or thermochemical conversion processes to produce added-value products [222]. Furthermore, multiple feedstocks could be combined for the generation of power, various distinctive biofuels and chemicals. All or part of the energy generated is used for the biorefinery operation. Therefore, an integrated biorefinery makes use of numerous conversion technologies and diverse mixtures of biomass feedstocks together at a single platform to yield an array of products, for instance, bioenergy, biochemicals and biofuels. The reuse

of the waste streams resulting from one conversion process within the bioenergy system results in the reduction of the environmental footprint. Besides, the efficient production of biofuels and valuable co-products leads to growing profits [239]. Thus, the integrated waste biorefineries concept should be adopted since it generates significant environmental and economic benefits.

4. Effect of chemical additives on WTE technologies

Due to the several obstacles hindering material recovery, the focus is directed, in the coming decades, on energy recovery as the preferred pathway for 3BMs waste treatment. The efficiency of these WTE technologies along with the product's yields and qualities are considerably influenced by the content of the inorganic or organic additives. Currently, few studies have inspected the inhibitors/catalytic effects of additives on both thermochemical and biochemical routes. Therefore, the fate of the most relevant inorganics during conversion and their influence on the different conversion processes are revised.

4.1. Biocides

During thermochemical conversion, the OIT, an antimicrobial agent having a molecular formula of C₁₁H₁₉NOS [240], is degraded at 342 °C into very toxic fumes of nitrogen oxides (NO_x) and sulfur oxides (SO_x) [241]. The 4,5-Dichloro-2-octyl-isothiazolone biocide forms dangerous decomposition products such as hydrogen chloride (HCl) gas, SO_x, NO_x and carbon oxides in the flue gas hence leading to equipment corrosion [242]. Propiconazole biocide, recognized as a demethylation inhibitor fungicide for wood preservation [243], decomposes at 320 °C and causes the emissions of hazardous vapor products (HCl and NO_x) [244].

During anaerobic digestion, OIT is biodegraded into carboxylic acids, sulfur, methylamines, and malonic acids. The resulting digestate cannot be composted since it threatens aquatic life [245]. Pentachlorophenol, a wood preservative wood was reported to be extremely toxic to anaerobic digestion even at low concentrations [246].

4.2. Flame retardants

Boron FRs such as boric acid and borax are the most commonly used substances in the various 3BMs formulations in the EU [247,248]. The boiling points of borax and boric acid are 320 and 300 °C, respectively [249]. However, the thermochemical conversion technologies take place at a temperature higher than the boiling temperature of the fire retardants, hence toxic fumes of boron and sodium oxide are emitted. Di Blasi et al. [249] have investigated the dynamics of boric acid decomposition throughout slow pyrolysis. Boron FRs accelerate the reactions of dehydration [250], decarboxylation and charring during pyrolysis [251]. The boric acid is seen to undergo endothermic water-losing reactions. These latter occur in two steps to produce metaboric acid (HBO₂) and water-free boron trioxide (B₂O₃), respectively [249,252]. It should be noted that the softening, melting and boiling temperatures of the boron anhydride are respectively 325 °C [253], 450 °C and 1860 °C [249]. Since thermochemical conversion processes occur at temperatures higher than the softening and/or melting points but lower than the boiling point of B₂O₃ [254], the irregular shape aggregates of this latter substance melt and form a glassy layer covering the biochar surface structure. This coating prevents the liberation of volatiles (alcohols, aldehydes, esters and ethers) from the biochar [249,251]. As a result of the stable bonds with cellulose impeding the mobility of B₂O₃ [249], the surface area of the biochar is significantly reduced hampering its use as absorbent [251] owing to pores blocking by B₂O₃ [249]. Because of the non-release of volatiles, the yield of biochar is improved. Besides, the higher calorific value is attributed to the higher energy in C–C bonds when compared to C–O bonds, as a consequence of the catalytic effect of FRs [251]. Nevertheless, the yields of the organic and gaseous phases are lowered. Besides, the fragmentation paths of cellulose, hemicellulose

and lignin are altered leading to a different composition of molecules in the bio-oil stream [249].

Throughout anaerobic digestion, boric acid and borax act as slowing agents lowering biogas generation as being moderately soluble in water [255].

4.4. Minerals

Undesired consequences are associated with the inorganic pollutants during pyrolysis. These compounds favor char formation at the detriment of the other phases. Despite being mainly trapped in the biochar as ash, the bio-oil yield and properties are drastically impacted [190]. Moreover, some toxic molecules are ejected in the gas phase throughout the primary aerosol formation stage [256]. Alkali metals, in particular Na and K, catalyze the degradation of the lignocellulosic feedstock at high temperatures. Alkaline earth metals such as Mg and Ca promote water formation in the pyrolysis oil. The transfer of these metals to the liquid fraction varies with their concentration. Aluminum and phosphorus elements have an inhibitory effect on thermochemical conversion. Silica alters the chemical pathways and the degradation rate. Depending on the type of biomass, the sulfur is transferred to liquid products (32–96% for agricultural wastes and 36% for wood wastes). The transfer of phosphorus to bio-oil is low (<2%) [257]. Meanwhile, the gaseous phase may be contaminated by sulfur molecules (SO₂, H₂S and COS), chlorine species and nitrogenous compounds (HCN, HNCN, NH₃). These latter are the precursors for NO_x that in turn leads to severe environmental problems. Even at low concentrations, chlorine species and SO₂ cause reactor fouling and corrosion [190]. During gasification, the minerals (alkali and alkaline earth elements) result in permanent catalysts deactivation, fouling of heat transfer surfaces, slag formation [258], the agglomeration of bed materials [259] and equipment corrosion. The higher the inorganic content in the feedstock, the higher the impurities in the syngas. Besides, the proportion of contaminants relies on the operating conditions [190]. The pollutants create particular challenges depending on the intended downstream application. Therefore, the purification of syngas is of great importance and is highly dependent on the emission standards and final utilization.

All through biochemical conversion processes, the existence of mineral molecules has been mainly linked to the inhibition of micro-organisms' growth, resulting in the decrease of productivity [260]. Furthermore, trace metals (Cu and Zn) were identified to be enabling biogas production [261]. These metals are recovered in the digestate in the form of stable inorganic precipitates and in the liquid phase as organic trace metals complexes. The disposal of these fractions into the environment as compost or for soil amendment has been limited in the EU countries owing to their risks on the land and aquatic life.

4.5. Mitigation solutions for additives

To mitigate the impacts of additives on thermochemical or biochemical routes, the pretreatment and post-treatment processes have to be implemented for lowering the concentration limits of the inorganic impurities and diminishing their effects during biomass conversion [262]. The mitigation of the effects of biocides and flame retardants applied in insulation materials is not well investigated in the literature. However, techniques applied for minerals removal from biomass can be suitable for this end. Subsequently, a brief description of these techniques is provided hereafter.

The pretreatment techniques are categorized into mechanical technologies (comminution and mechanical sieving), thermal (ultrasound/microwave irradiation, steam explosion/liquid hot water extraction and torrefaction) and chemical (water leaching, acid washing and base washing) [190].

The mechanical sieving technologies reduce the size of the feedstock particles, hence segregating the minerals in different fractions and decreasing the ash content [263]. The thermal technologies are driven

by thermal energy. Due to high temperatures (160–300 °C), several chemical reactions occur and change the properties of the biomass, thus reducing the ash and inorganic contents. Hot water extraction was noticed to be the most efficient process for eliminating various alkali metals [264]. The chemical technologies consist predominantly of washing the biomass with water, dilute acids (such as hydrochloric, hydrofluoric, sulfuric and nitric acids) and bases (ammonium hydroxide and sodium hydroxide) for inorganic content reduction. The acid washings enhance the depolymerization of hemicellulose and cellulose, impacting positively the pyrolysis of the washed biomass [265]. However, acid demineralization has been distinguished to disrupt the chemical structure of the biomass [265,266]. Due to rinsing requirements, the chemical processes generate a huge amount of wastewater needing further treatment [190].

The leaching and dewatering processes enhance feedstock properties via the removal of water-soluble alkali and alkaline earth elements. The washing of rice and wheat straws removes alkali metals (K and Na) and chlorine [267]. The dewatering followed by water rinsing performed on fine banagrass samples reduces the ash content by 45%. Accordingly, nearly all of the chlorine, 90% of K, 55% of S and 70% of Mg, Na and P are removed [268]. Yet, these strategies present several drawbacks such as the reduction in the overall efficiency because of additional drying of wet biomass and consequently higher operational costs [190].

Post-treatment approaches include the purification of the solid, liquid and gas streams. The removal of contaminants is performed by numerous technologies to meet stringent concentrations for downstream utilization [190]. In the context of pyrolysis and gasification, post-treatment technologies, summarized in Table 8, are needed for purifying the products from undesirable inorganic species.

5. Conclusion and future research

This review presents a literature survey on the common types of biomass-based insulation building materials. This article summarizes the forms of the insulators, their applications, their production and installation techniques, their compositions, their prices along with their current and future volumes. A high priority was given to the EoL and treatment scenarios as a significant volume of biomass-based insulation wastes (185,300 tons) is expected to be generated starting from 2050. This review article resumes the marginal environmentally efficient recovery routes (reuse, recycling and composting) for some bio-based products. Besides, the technical and financial constraints limiting these strategies are discussed.

The innovation of this study lies in suggesting the application of

Table 8
Post-treatment technologies for pyrolysis and gasification's products [190].

Purified stream	Post-treatment techniques	Advantages	Drawbacks
Syngas	Cold gas filtration through a solvent (water)	Increase the syngas quality Decrease inorganics (NH ₃ , HCl, H ₂ S, ...)	Loss in efficiency due to cooling
	Warm gas filtration through sorbents (activated carbon)	Adsorption of inorganics	Loss in efficiency due to cooling Uncontrolled deposition of inorganics on surfaces Corrosion
	Hot gas filtration through sorbents (activated carbon)	Adsorption of impurities Increased efficiency and reduced waste streams	Thermal instability Low removal efficiency
Liquid	Bio-oil filtration	Reduce alkali and alkali-earth metals	Filter clogging by char
Solid	Two-step water leaching	Reduce inorganic contents	Large quantity of wastewater generated

sustainable Waste-to-Energy technologies, via thermochemical or biological conversion routes, as the paramount strategy for waste minimization. The WTE processes will prevent the accumulation of 4.1 million m³ of insulation wastes in landfills by 2050, hence the alleviation of the landfill costs reaching 11.1 million euros. The conversion of bio-based building wastes into heat, electricity, alternative fuels and materials to meet the market demand will generate significant revenues. With this option, around 315,000 tons of CO₂ and 75,000 tons of fossil fuels are estimated to be saved per overall tonnage of waste valorized corresponding to 78.9 million euros. The energy recovery could be successfully integrated with the waste biorefinery concept for the maximum production of valuable products. This concept generates considerable environmental benefits and economical profits; endorses the achievement of sustainable waste management and boosts the circular bioeconomy.

Future research should be directed towards investigating the technical feasibility of the various WTE technologies on the different families of biomass-based insulation materials by carrying out laboratory experiments and upscaling. The optimization of the WTE conditions (temperature, residence time, carrier gas, pressure, ...) needs to be conducted for each material. Then, an extensive characterization of the resulting products (char, bio-oil and gas) is needed to check if the end-use products meet the regulatory standards. Furthermore, the market values of different products (energy carriers, chemicals, fertilizers, activated carbon, ...) should be estimated in order to compare the optimal solution paired with specific needs of different case studies.

Further studies have to be dedicated to assessing and mitigating the influence of additives (adhesives, flame retardants, ...) on the yield and the quality of the obtained streams along with the conversion processes. Another concern that should be addressed is the environmental and economical benefits of WTE technologies in line with the local waste management strategies, the infrastructure requirements and the climate and geographical conditions of French regions. By conducting a LCA on each technology, this will assist in decision-making for the selection of the proper waste-to-energy process.

Technological advancements, predominantly in the pretreatment and post-treatment phases, are essential to enhance the yields and qualities of the purified syngas and the upgraded bio-oil for reaching economic viability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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