# Thermal and Acoustic Building Insulations from Agricultural Wastes

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**Abstract**
Global population growth and economic growth increase the demand for more buildings and thus more construction materials. Increases in production of construction materials lead also to greenhouse gas emission rise and depletion of natural resources. One of these materials is insulation, which increasingly plays a vital role in the energy performance of buildings and in the process reducing negative environmental impacts of the built environment. A number of studies have focused on finding substitutions for petrochemicals as a source for manufacturing building insulation. Some investigations have identified insulation materials that have lower environmental costs, for example, those that are made

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of natural or recycled materials. Manufacturing building insulation from agricultural by-products is one such approach. However, these are in their early stages of development, and there is a long way to have them on the market.

Alongside identifying matters that require additional research to enhance technical reliability, this study explores issues that can improve the market viability and help make natural and recycled materials more attractive alternatives. There are some common themes among these materials and earlier studies have revealed that each of these agricultural wastes has some advantages that can be exploited for specific purposes alongside disadvantages that must be overcome. From another perspective, it is important to compare the performance of these new materials with that of more conventional options. This is one of the first steps needed to modify the industry. This chapter refers to earlier studies discussed in the literature in discussing the technical behavior of bio-based insulations in four categories: thermal, acoustic, environmental, and mechanical behavior. This research reveals the hotspots where evidence is currently lacking and how to find evident opportunities for this market, thereby suggesting where future research should be directed.

## Introduction

A backlash from modern cities to traditional houses which were integrated with environment as an organic being is going to be a trend since the conservation and sustainable movement have been established. This movement is about considering the impact and consequences of a product or service on environments in which people are only one of the inhabitants, throughout production, use, and disposal. Houses are part of the local ecosystem, so they should be built by local natural materials, dependent on local energy, food, and water sources. As such, wastes will also be recycled locally.

This return to past practices is in large part for the health-giving qualities of the system. Consequently natural building materials, those that are clean, compatible with the environment, and resistant to harmful micro-organisms are considered desireable.

Agricultural wastes, at first sight, do not seem to be a likely candidate for building construction; however, with a review of some traditional techniques, we find out they had typical use in the construction. For example, reed in Iraq or Egypt, palm or banana leaves in Africa, and bamboo in Eastern Asian countries have long histories of use. Presumably these kinds of natural materials with all of their benefits have fallen out of favor because of artificial fibers' boom.

Ecological and sustainable material may have some certain common features: renewable, abundant, with low environmental impact, energy efficient, with low-energy consumption from cradle to gate, local, durable, easy to maintain and repair, socially sustainable, reusable, recyclable, and with low waste. Considering these criteria will have a significant benefit in the sustainability spectrum of the whole building [1].

Natural fibers are among the materials that can actually have positive environmental impact; if we grow them organically and send them to a sustainable manufacturing process to be converted into a high-performance and energy-efficient product with other natural components, they can also be biodegradable at the end of the life cycle; in other words, they turn back to the earth. Natural fibers, in this study, are nonedible plant parts that are left in the field after harvest and also by-products and leftovers of manufacturers who use these fibers.

Major driving forces behind the idea of using agricultural crop residues as natural fibers are ongoing depletion of natural resources, new regulations on using synthetic fibers, growing environmental awareness, and economic gain.

Although there are some examples of bio-based solutions in the market such as Knauf and straw bale, and others are emerging, such as coconut wood composite, cork, and almond polymer composite, there is still a long way until they become conventional items in the list of building materials.

## Natural Fibers

After a review of international topical background on agricultural wastes and natural fibers, some similar characteristics are revealed. A summary of these common themes is classified in Table 1 below. Inherent properties of natural fibers make them good options for thermal and acoustical insulators. However, these inherent properties are not always helpful, since these natural fibers have nonhomogeneous structure, and still we do not have reliable theoretical models to explain their behavior; also a wide range of tests with different configurations and binders should be undertaken to identify reliable combinations [2]. Therefore, the manufacturing process after investigations is a defining factor which affects the characteristics of insulation materials. Each of agricultural products can be used for different purposes according to their specific characteristics. Climate and geographical situation are important because using local materials has many benefits such as less transportation.

Still, more studies are required to support these natural fibers from every aspect. Nevertheless, comparing results with similar conventional alternatives in the market is one of the first approaches that comes to the mind. Reviewing related literature indicates that environmental impacts and economic feasibility are two steps that should not be neglected [3].

Positive impacts on human health and psyche are two potential advantages that future studies should focus on according to several earlier studies [5, 6], bearing in mind that some issues such as resistance against fire and degradation due to moisture, bacteria, mildew, and fungi affect the long-term performance [7].

## Context

### Sustainable Transition

The world around us won’t work as before, nor as future, it changes. One of the roles of science is to give a plausible image of the future developments to people and particularly to decision-makers. Sustainable transition is a coevolution according to

**Table 1** Advantages and disadvantages of agricultural by-products as insulation [4]

| Advantages | Disadvantages |
|---|---|
| Low thermal conductivity<br>Self-link<br>Fast renovation<br>Abundant<br>Natural<br>High specific heat<br>High damping of vibration<br>Biodegradable<br>Cost-effective<br>Lower environmental impacts<br>Energy efficient<br>Less emission<br>Renewable resources<br>No skin irritation<br>Nontoxic | Non-load bearing<br>Thicker<br>Treatment<br>Nonhomogeneous<br>Variation<br>Unsuccessful theoretical models<br>Non-fire resistant<br>Hazardous additives<br>Contaminants<br>Influenced by weather<br>Lower durability |

bridging between various scientific disciplines. Two broad categories that led to transition research were first innovation research and secondly environmental studies and sustainability sciences [8]. Rotmans says “The new equilibrium is a dynamic equilibrium, i.e. there is no status quo because a lot is changing under the surface” [9].

Usually, there is some inertia that hinders the transition process, including historical investment and socio-institutional routines since they are stable areas of past practices. However, socio-technical and socio-ecological transitions have this dynamic to adapt change over time. For shifting to a more sustainable transition, this process should be long-term, multidimensional, and fundamental in order to have a sustainable production and consumption [10]. Sustainable transition helps to understand broad trends of change in terms of using sustainable building materials.

## Estimations

Each region has specific agricultural production according to the climate and the geographical situation. Hence, feasibility studies of innovations new to humans and their environments need to be carried out locally and comprehensively. In addition, we should always consider that they are agricultural residues so a lot of factors are involved in decision-making about using them. Annual crop yields are variable year to year depending on different issues like climate and precipitation pattern, soil properties, plant varieties, farming techniques, etc. Since we are talking about agricultural crop residues, we should know that the amount of residue produced is related to plant variety, crop yield, harvesting techniques, and the cutting height. The availability, or in other words the permission to remove these residues, has an influence on the fertility of the land and the use of these residues in other industries. Estimations are only that, predictions based on information to hand, and these can vary year on year or due to the influence of some unforeseen event. Some of the

**Table 2** Factors of estimating agricultural residues, adapted from "Assessment of the availability of agricultural crop residues in the European Union" by Scarlat et al. [11]

| Factors taking into account for estimating agricultural residues |
|---|
| Types of crops and their required attributes such as area of crop production |
| Yields of crops |
| Crop residue-to-yield ratios |
| Considering requirements of soil conservation and environmenral impacts of crop residue removal rate |
| Considering other competitive uses of crop residues such as mushroom production |

key issues to consider when estimating the potential use of agricultural residues are shown below in Table 2, suggesting there can be significant annual variation in the quantity of agricultural crops .

Removing residues from land can have some consequences because they have a role in protecting the soil from erosion, maintaining or increasing soil organic matter, maintaining mineral nutrients in soil, and improving water retention. Removing a part of these residues from land may be enabled by techniques such as by conservation tillage, crop rotation, the addition of manure, and fertilization. Some references have provided a guide for residue-to-crop production ratios and sustainable removal rate [11, 12].

Agricultural crop residues have different competitive uses such as animal husbandry or horticulture/mushroom production or even bioenergy plants. Therefore, evaluating them in terms of benefits to be used as a primary material for building insulation industry comparing to other uses is essential. Using agricultural residues for building insulation is not only a good opportunity but also a strong competitor for other uses. Thus, with a conservative basis, we should take into account various agricultural, environmental, and economic constraints and competitive uses.

In order to have a correct estimation about using agricultural residues for any purpose, considering these issues is important: resources (quantity, multi-annual yield variation), logistics (storage, security of supply, harvesting period, and transportation distance), and technological (available technologies), economical (costs of resources), and social issues (perception and attitude of farmers) [11].

Studying the history of using these agricultural by-products and their agricultural situation will be helpful as a means of clarifying potentials. In general, a short historical and agricultural background for each material will be mentioned in the following sections that can relate to the current and future status in the discussion.

## Stakeholders

There is extensive evidence indicating that stakeholders improve decision-making process by adding new information, ideas, and analysis. The complexity of sustainable transition is because of the large number of actors and their interests. Stakeholders' participation is a vital element. This engagement brings nonscientific knowledge to this process, in other words practical knowledge and experience [13].

Although stakeholders have this potential to ease the way toward sustainability in the construction industry, they have different and sometimes unclear roles to pursue when it comes to choosing materials [14]. Specifically, for the development of new sustainable products, the cooperation of multiple stakeholders is a debatable issue which has not been studied widely. Freeman defined stakeholder as “any group or individual who can affect or is affected by the achievement of the organizations objective” [15]. In this study, in the construction industry, for using building insulations which are made from agricultural residues, stakeholders are consumers, manufacturers, suppliers, regulators, NGOs, architects, and designers.

Governments become involved by formulating the vision and inspiring other actors and the learning process. This will include creating boundaries for the market and more directly stimulating experiments and developing new partnerships. Thus, the government has a leading role: facilitator, stimulator, controller, and director. However, there are some limitations such as external factors, political structure, and sociocultural factors [9]. One of the government’s interventions is waste reduction policies, and the other one is production schemes which are encouraging directly or indirectly.

Environmental activists and NGOs are stakeholder groups that are driven by community actions, and they can have a great influence on changing public attitudes and persuading consumers toward using more environmentally sustainable materials, promoting recycling, reuse, composting, waste reduction, waste education, and fostering partnerships [16, 17]. Unfortunately, this emphasis on sustainable and green products is not on building materials yet [18].

One of the key stakeholders in the construction industry is the architect or designer; in the case of using insulations that are made from agricultural residues, they can be key stakeholders too because this is the architect or designer who selects materials and gives a proposal. They are prime candidates to take this responsibility at the first stage of designing a building. Hence they should have the understanding of the importance of this substitution in the production phase of materials.

This transition is still in the first phases, so there is no legal requirement to use them, and in this situation, personal interest and the ideas that are driven by the design team and clients can be the main impetus for this change [19]. Based on earlier studies of buying behavior, it is customers who dictate (or define) the values of the market which is a preference for a sustainable product in this study.

The construction industry has recognized the future limits of natural resources and is encouraged to increase the percentage of recycled content in its products [20–22]. Practically, firms should try to meet the needs and expectations of stakeholders socially and environmentally too, and this means that it is going to change from a mere moral issue to an obligation for firms. Such a business can be called a green business that meets the triple bottom line of sustainability.

## Characteristics

Natural fibers, plant fibers, or vegetable fibers which are made of cellulose are found in cultivated crops either in seeds or stems (bast). Studying their technical information is one of the essential steps. This section reviews the current research on unconventional bio-based insulation materials under four categories: thermal, acoustical, environmental, and mechanical behaviors.

## Thermal Insulators

Reducing the transmission of heat through the building envelope is the reason to use thermal insulation. Thermal performance can be measured by different parameters; thermal "conductivity" and its reciprocal "resistivity" are the ones mostly reviewed in this section. The thermal conductivity of insulations should be less than 0.07 W/m K to be considered as an insulator [23]. Conduction, convection, and radiation heat loss are involved in thermal transmittance. Another parameter which is measured in some studies is "specific heat" that means the ability of a material to store heat, termed. The following section reviews thermal characteristics of different potential agro-waste materials and summarizes the most common ones in Fig. 1 and Table 3. The very good thermal performance of flax, fique, hemp, pineapple, coconut, cattail, bagasse, and rice suggests that additional research into other behaviors would be beneficial.

Corn is one of the most widely planted crops in the world that surpass the production of some other major crops like rice and wheat. It is cold-intolerant, and because of its shallow roots, it is dependent on soil moisture. The price of this product is affected to a certain degree by the use of maize for biofuel production. According to the obtained product yields and quality in laboratory scale, a lot of research has been carried out on them. The low density, foam-like core of the corn cob makes this by-product a good alternative for insulation. The thermal conductivity of corn cob particle sheets formed by wood glue is comparable with XPS [24]. *Tabique* is the name of a traditional building construction with corn cob based on earth and timber frames that are common in the northeast of Portugal; this technique shows that corn residues have a history to be used efficiently. Corn microstructure, elementary chemical composition, and superficial temperature made it applicable as building thermal insulation [25]. The manufacturing process is one of the most important factors in making them a competitive thermal insulation [26]. Some studies tested examples which are a mix of corn and other materials, such as tissue paper [27].

Durian is tropical fruit with spiky green to brown skin, and it can grow as large as 30 centimeters long and 15 centimeters in diameter, only in tropical areas. The price of this seasonal fruit is relatively high. The fibers of this plant have been used to make fiberboards that after chemical modification which is adding adhesives showed good physical properties as insulations compared to medium-density fiberboards [28].

Coir or coconut fiber is a brown natural fiber extracted from the husk of coconut, found between the hard, internal shell and the outer coat of a coconut. But pith is the powdery material resulting from the processing of the coir fiber. Ropes and cordage are among the ancient uses of coir. Coconut pith and fiberboards also were found as good thermal insulation materials because of low thermal conductivity and acceptable physical values in similar studies [29, 30].

Fique is a natural fiber taken from the leaves of the fique plant. This plant is very adaptable to different ecological conditions and annually can produce 1 to 6 kg of

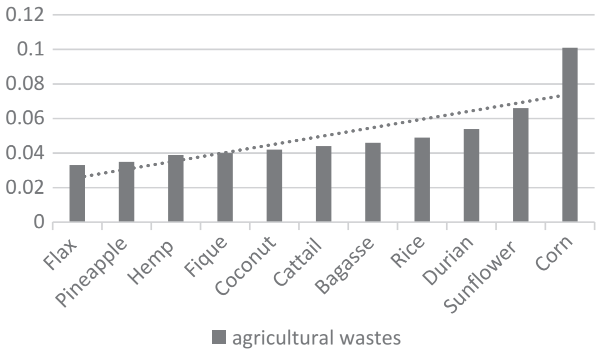



**Fig. 1** Thermal conductivity of some popular agro-waste products

**Table 3** Thermal conductivity of some popular agro-waste products

| Product | Conductivity W/m°K | References | Product | Conductivity W/m°K | References |
|---|---|---|---|---|---|
| Corn | 0.101–0.139 | [24–27] | Sunflower | 0.0656–0.077 | [36, 37] |
| Durian | 0.054–0.1854 | [28] | Rice | 0.049–0.063 | [30, 38, 39] |
| Coconut pith | 0.0416–0.086 | [29, 30] | Bagasse | 0.046–0.068 | [29, 40] |
| Fique | 0.04–0.08 | [31] | Cattail | 0.0438–0.0606 | [44] |
| Flax | 0.033–0.09 | [7, 32, 33] | Pineapple | 0.035–0.057 | [45, 46] |
| Hemp | 0.0393–0.123 | [7, 33–35] | | | |

fibers. It has been traditionally used for the manufacture of packaging and cordages. Compared to mineral wool as a comparable option to fique, fique fibers covered by polymer showed good thermal behavior [31].

Flax can be cultivated in cooler regions and it is traditionally used for bedsheets, underclothes, and table linen. Also, they can be a nutritional supplement and an ingredient in many wood-finishing products. These fibers are smooth and straight which are taken from the stem of the plant and are two to three times as strong as those of cotton. Flax tow is a coarse, broken fiber, removed during processing of flax. We can make self-linked composite flax tow with significant thermal performance, depending on the grinding size. This is an interesting experiment, because by increasing the grinding size, thermal conductivity will decrease and acoustic absorption coefficient will increase [32]. These fibers can be used separately or blended with other fibrous materials such as hemp or jute in the form of a mat or loose-fill samples [7, 33].

Hemp is one of the fastest-growing plants and has been used extensively throughout history in rope, clothes, food, paper, and textiles and from many years ago in plastics, insulation, and biofuel industry. Industrial hemp is also recognized as a fully comparable option to common insulator materials. However, they require treatment like other vegetable fibers that improve physical behaviors [7, 33, 34]. This plant is one of the popular natural fibers that has been studied vastly by different authors, resulting in different samples with different properties, like the hemp bast lime biocomposite, a low-density material [35].

Sunflower has erect rough-hairy stem, reaching typical heights of 3 meters, and its leaves are broad, coarsely toothed, rough, and mostly alternate. It can be cultivated in temperate regions and some tropical regions. We can make a medium-density material made from a cake generated during the bio-refinery of sunflower oil, and the lowest density has the lowest thermal conductivity that can be used as a loose fill in the ceiling [36]. Another way of using this plant for insulation is utilizing crushed stem particles and chitosan as a binder [37].

Rice is labor-intensive to cultivate and requires ample water but can be grown practically anywhere. It can grow to 1–1.8 m with long, slender leaves 50–100 cm. Rice husks or hulls are generated during the first stage of rice milling, but paddy straw is produced after the grains are threshed [30, 38]. Rice can be added as an ingredient to wood fiber composite, and this composite board met the standards well after measuring the thermal conductivity and thermal diffusivity [39].

Bagasse is the residue left after sugarcane stalks are crushed. As a by-product of cane sugar factory, every 10 tons of sugarcane crushed produces nearly 3 tons of wet bagasse, containing around 30–40% of “pith” fiber derived from the core of the plant. It is commonly used as biofuel, pulp, and building materials. It has a low thermal conductivity in the shape of a loose-fill insulation [29]. Also, a binder-less low-density board made of coconut husk and bagasse was tested, and the results were close to other fibrous materials and mineral wool [40].

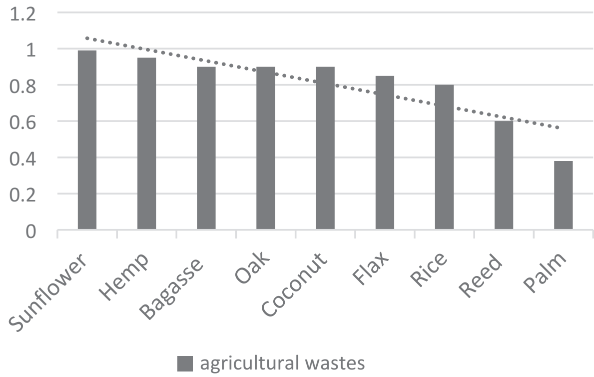
The fast regeneration of reed makes it a good material for insulation and is used as thermal insulations in some countries where it is abundant. Reed is a grasslike plant which can be grown in wetlands throughout temperate and tropical regions. Stems grow to 2–6 m with long leaves 20–50 cm. Many cultures have used reeds in the construction of buildings. Reed panels have acceptable thermal conductivity. Nonetheless, there are different results by different authors based on their measurement method [41, 42].

Palm trees are restricted to tropical and subtropical climates and are distinguished by their large, compound, evergreen leaves. The date palm had a tremendous effect on the history of the Middle East. Practically all parts of the palm yielded a variety of products. There are a number of earlier studies of the physical properties of palm, including thermal conductivity [29]; when used in combination with other products such as binders, they can be good candidate for developing insulation material. An improtant consideration is the fiber’s orientation [43].

Cattail grows in a variety of wetland habitats with a rapid growth cycle and often excludes other plants with their dense canopy. Its leaves are hairless, linear, and alternate. Every part of this plant has multiple uses, such as making chair and paper. Besides it can be used as thermal insulation in buildings as an organic alternative. Cattail has better thermal conductivity values compared to other natural fibrous materials and good energy saving as an insulation component with published patent [44].

Pineapple is a tropical plant with a range of residues. Leaves are used to produce the textile, and the fiber can be used as a component for wallpaper and other furnishings. Leaves with a natural rubber latex can make insulation boards with a high feasibility to be a substitute for synthesis insulations [45, 46].

**Fig. 2** Sound absorption coefficients of some popular agro-waste products




## Acoustic Insulators

Most of the experiments on insulations with agricultural by-products are carried out to make airborne sound insulation which can be measured by weighted sound reduction index, transmission loss, and sound absorption coefficient. Acoustic insulators can reduce airborne or structural born sound. Most of these studies have been focused on sound absorption as can be seen in a summary of results in Fig. 2. These parameters can be measured in a reverberation room and/or impedance tube based on the size of the samples through different methods. Studies have also shown that palm, reed, and rice are among the materials that hold promise as acoustic insulators, largely because of their good sound absorption coefficients (Table 4).

Corn cob particleboard is one of the few examples of insulations which is made to reduce structural born sound and has a highlighted potential compared to traditional and natural insulation products. The impact sound insulation gain for these boards is estimated to be 30 dB [47].

Self-linked composition with flax tow can be used as a sound absorbing panel by considering the significant effect of the manufacturing process and the compaction rate. However, they can improve in terms of mechanical resistance for construction purposes [32]. Also, they showed some results similar to fiberglass [48]. Besides reducing sound, this material has damping behavior because of its structure, and some tests indicated that it can be an alternative in high-damping composites not only for building acoustic insulation [49].

Hemp is one of the materials that has been put in both theoretical predictions and laboratory measurements. Results indicate hemp has good sound absorption properties and good reverberation characteristics [48]. Hemp also can have satisfactory performance in high-damping composites [49]. Different studies with various combinations proved that hemp fibers have potential to be an acoustic insulation [2]; however, results vary and can be improved in combination with other materials over wider range of frequencies [50]. Composite board made out of wood chips and fibers, hemp flakes, reed, and wool waste fibers as biodegradable materials with different percentage has been tested and indicated that the density had no influence, while the component of wool brought good acoustical results for the composites. In

**Table 4** Sound absorption coefficient of some popular agro-waste products

| Product | Average sound absorption coefficient | References | Product | Average sound absorption coefficient | References |
|---|---|---|---|---|---|
| Flax | 0.5–0.85 | [32, 48] | Rice | 0.02–0.8 | [39, 55, 56] |
| Hemp | 0.45–0.95 | [2, 48, 50, 51] | Oak | 0.9 | [2] |
| Reed | 0.25–0.6 | [2, 50, 52, 53, 60] | Coconut | 0.5–0.9 | [2, 56] |
| Bagasse | 0.15–0.9 | [54] | Palm | 0.38 | [59] |
| Sunflower | 0.86–0.99 | [48] | | | |

this study, based on a practical view, the noise level of urban context has been considered as a liable scale, and the absorption coefficient of these composites was in an acceptable range [51].

Different investigations with various configurations have been done on reed fibers [50], and in the test room, reed fibers in jute bags demonstrated an effective treatment [52]. Reeds and rye straws were compared to show the effect of different morphologies of samples on the acoustical behavior [53]. Samples of a granular mix of bark and wooden parts with cane or reed fibers with binders were tested and revealed that increasing the thickness makes better sound absorptive panels that come along with theoretical models [2].

Sugarcane bagasse with resin was used to make a three-layer insulation board before the sound absorption characteristics and other related physical and mechanical properties were analyzed [54].

The acoustical performance of sunflower without binder has been predicted by theory and measured in the laboratory. Results indicated that its performance is dependent on whether bark or pith is used in the samples [48]. There is another methodology to test samples which is done on sunflower stem with bio-based binder by ultrasonic waves [37].

Rice straw board samples with higher fiber content and thicker had better acoustical performance. Paddy straws in another study had a better sound absorption [55, 56]. Based on Liu study, both rice straws and wood fiber boards had good sound absorption coefficients. This material can be mixed with wood particles too and result in better sound absorption, because it has higher absorption over medium and high-frequency ranges compared to wood particleboards [39].

Cork oak, which is commonly used as the primary source for wine bottle stoppers, cork flooring, and cores of cricket balls, grows to up to 20 m. Natural stands of cork oak can support diverse ecosystems. The quick regeneration of this oak makes it successful in the fire-adapted ecosystems of the Mediterranean forests. Thick and rugged bark can be harvested every 7 to 10 years to produce a renewable resource of cork. This harvesting does not harm the tree and can be done about 12 times in its lifetime. This harvest which is entirely without machinery benefits a lot of industries such as insulation panels, floor and wall tiles, and sound-proofing in the car. Studies on oak cork's sound absorption have shown that in different frequencies based on the grain size absorption changes but in high frequencies, this change is more considerable. Also, theoretical models were not successful and did not confront with tests [2].

Coconut fibers can be used as an alternative for acoustic insulation [56] and when packed in large, thick bales without binder demonstrated remarkable results [2]. Earlier studies made with binders also demonstrated had lower sound absorption coefficients, and overall pattern was demonstrated by theoretical predictions. Similar to other studies, adding additives improved the performance particularly in low frequencies [57]. Some studies focus on empirical equations; however, this effort greatly depends on the type of the coir fibers to be effective [58].

Windmill palm with long leaves of 140–190 cm, coarse but very strong, is used for making rope, sacks, and other coarse cloth. This type of palm grows further north in the Mediterranean. It can be combined in the form of the non-woven mat with a coating of polyvinyl alcohol for acoustical purposes. This coating significantly improved the absorption of samples, and it has been appreciated as a high-performance and cost-effective sound insulation [59].

## Environmental Impacts

High-quality products can be made from plant fibers; however, from the first step, farming, then transportation, and manufacturing, every taken method is important in knowing them as an environmentally friendly product. Considering every step of the life of these materials, they usually have low environmental impact compared to conventional alternatives in the market [61].

The environmental impacts of insulations like other materials are evaluated through life cycle assessments (LCA) that include the entire life of materials and sometimes part of it. The aim is to deepen the knowledge of energy and environmental specifications in designing buildings. Defining the system boundary and normalizing to the functional unit are two first steps. For example, for thermal insulations, this functional unit is equal to the mass of the material which provides a thermal resistance of $1 m^2K/W$. Energy and greenhouse gasses are two main indicators of environmental impacts (Fig. 3).

EPS is an example of building insulation which requires a high level of manufacturing processes. Unfortunately, it is one of the most common used insulations, comparing to insulations with natural sources such as cork, wood fiber and sheep's wool, or specifically for this study insulations made of recycled agricultural fibers. EPS or polyurethane emits on average 7 kg $CO_2$-Eq/kg, while cork emits 0.807 kg $CO_2$-Eq/kg, and obtaining cork in the forests does not only damage the tree but also contributes to the maintenance of the ecosystem, and more than 50% of primary energy demand is for biomass origin, and actually this impact is very low [62].

In another study, expanded cork agglomerate (ICB) compared to extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PUR), and expanded clay lightweight aggregates (LWA) showed a low contribution to the impact categories and low consumption of fossil fuels [63].

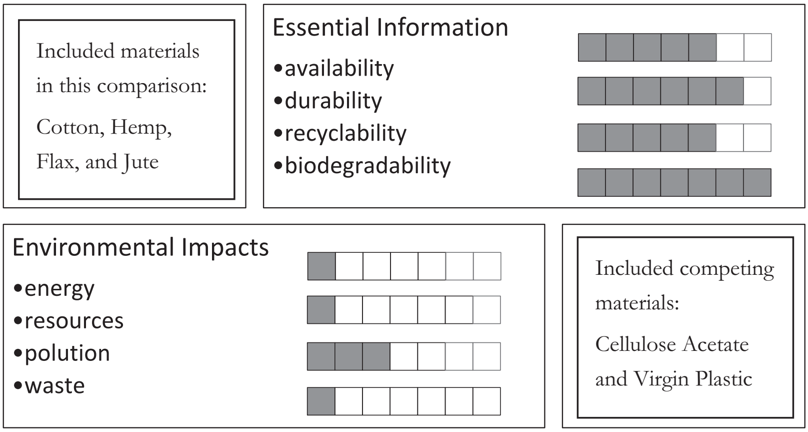



**Fig. 3** Essential information and environmental impacts of some common natural fibers, adapted from "Sustainable materials, processes and production" by Thompson R and Thompson M [61]

Some complete environmental analysis has been done on flax and cork in comparison to other commercialized building insulations [64–67]. Not only building construction industry but also all other industries care about their environmental impacts, so sometimes we can find their inventories and inputs of field production, system boundary, and methodology for finding the environmental hotspots through the life cycle to help the insulation industry as well [68–70]. These natural fibers lower environmental impacts through their production phase, but they can have more benefits when it comes to energy efficiency and fewer emissions in the use phase [6]. However, adding flame-retardants to flax insulations make them hazardous for the environment [3] which may have other solutions in the future.

Not all of the LCA studies involve the whole life cycle but they are still useful (Table 5). For example, there are some studies which focus on the field production of hemp [71]. Some include other stages such as insulating performance and energy savings [72]. Based on the results of many studies, eliminating binder or using natural binders is a very important factor to lower environmental burdens [67] such as using lime which indicated fewer impacts [35]. There are inventories for palm in other industries which can help life cycle analysis of it as a building insulation material [73].

## Mechanical and Physical Behaviors

This section provides a summary of all other characteristics that insulations should have other than thermal and acoustical performance, such as structural performance, fire resistance, and vapor permeability. Apparently, there is a wide range of these parameters, so in this study, almost only research that is related to materials in previous sections is collected (Table 6).

**Table 5** Environmental assessments of some popular agro-waste products

| Materials | Cradle to gate | Other industries | Specific stages |
|---|---|---|---|
| Flax | ■ | ■ | ■ |
| Hemp | ■ | | ■ |
| Reed | ■ | | ■ |
| Palm | | ■ | ■ |
| cork | ■ | | ■ |

**Table 6** Physical and mechanical properties of some popular agro-waste products

| Product | Flexibility and strength | Fire resistance | Water or vapor absorption and permeability | Microbiological resistance | References |
|---|---|---|---|---|---|
| Bamboo | * | | | | [74] |
| Corn | | * | * | | [26, 27, 30, 75] |
| Durian | * | | * | | [28, 30] |
| Coconut | * | | * | | [28] |
| Fique | * | | * | | [31] |
| Flax | * | | * | * | [7, 32, 33, 49, 76] |
| Hemp | * | * | * | * | [34, 48, 77] |
| Rice | * | * | * | | [30, 39, 78] |
| Groundnut | * | | * | | [30, 78] |
| Cattail | * | | * | | [44] |
| Pineapple | * | * | * | | [46] |

Bamboos are among the fastest-growing plants in the world and grow in warm and moist tropical and warm temperate climates. These evergreen plants have hollow internodal regions in the stem and have a high compressive strength and tensile strength which is a good reason for being traditionally used as building materials (scaffolding). For this reason, they must be harvested when the culms reach their greatest strength. Laminated corrugated boards made from bamboo waste and wood particles have been tested in terms of mechanical and physical behavior. Results showed that it can be an optimum alternative with lower cost, depending on the grain orientation and density [74].

Corn cob is traditionally used in Portugal, and recently some studies have been done on chemical compositions and physical properties of corn cob panels to show the adequate capacity of it for building applications [26]. In addition to corn cobs, corn stalk pith can be used to develop some low-density fiberboards with wheat by using a modified adhesive and binder. These particleboards may be applied for ceiling or cover materials since they cannot be load bearing [75]. Also, corn peel with tissue paper waste can be a new particleboard that can be laminated with recycled polystyrene and make an inexpensive environmentally friendly building material, while the performance depends on the ratio of ingredients and density [27].

Durian peel and coconut coir like other natural fibers can pass most of the mechanical and physical tests by chemical modification [28]. The coconut pith board has also shown satisfactory results in mechanical and physical performance [30].

Comparable properties of fique fibers to mineral wools, low cost, and mechanical resistance present it as a future alternative [31].

Flax tow is one of the natural fibers that can be used to make a self-linked particleboard which is an advantage in terms of environmental aspects [32]. A needle punched non-woven sample of flax with different chemical compositions was tested to check the mold growth. By using the molecular method, it was proved that the tannin-based and pretreated samples could resist against mold growth [76]. In another study, flax, hemp, and jute fibers are used to make particleboards with bicomponent fibers as a binder, and they had similar results to other common insulating particleboards [7]. Combustion resistance of flax and hemp by adding boric compounds was examined, and other quality properties of them have been collected from previous studies to support these natural fibers as suitable materials for insulations, but the risk of microbial and contaminants should be considered [33]. Besides normal acoustical test, damping decrement, resonance frequency, and ultrasound velocity are some complementary tests that have been done for flax, lyocell, and hemp, and results showed that they can be high-damping bodies [49].

Hemp can be used itself as an insulator material [34]; however, hemp concrete (hempcrete) is one of the composites made of this natural fiber and has been the topic of many studies [79, 80]. The mechanical behavior of starch-hemp concrete as a filling building material has also been analyzed [77]. Hemp with lime composites behaves well and has the benefit of lower cost in comparison to common alternatives but with different properties [35]. Some investigations on physical properties of hemp, flax, rape, and sunflower fibers demonstrated valid results to include them as good insulation materials [48].

With the purpose of producing an internal partition wall cladding for residential buildings, renewable and recyclable medium-density particleboards made of maize cobs, rice husks, and groundnut shells with a natural binder were prepared. Most of the materials did not show satisfactory results as a structural element, but they can be good non-load bearing components due to the minimum requirements of non-load bearing walls [78]. These materials have been tested separately too [30]. In an effort to make particleboards with rice straw and wood fibers, results of dimensional stability and moisture capacity were acceptable but not the flame retardancy of panels [39].

Narrow-leaved cattail fibers [44] and pineapple leaves can also be excellent materials for thermal insulations based on the mechanical and physical test results [46].

## Evaluation Criteria

As noted, agricultural crop residues in this study are nonedible plant parts that are left in the field after harvest and also by-products and leftovers of manufacturers who use these fibers. Based on different studies, the evaluation criteria for potential agricultural crop residues are as follows [11, 81]:

1. Resource availability: locally grown, yield high enough to produce, multi-annual yield variation
2. Logistics: storage, security of supply, harvesting period, and transportation distance
3. Technical viability: acceptable performance in use, e.g., thermal, acoustical, and physical
4. Environment friendly: acceptable LCI (environmental lifetime cycle impact)
5. Infrastructure needs: technically possible to grow with existing technologies and processing facilities
6. Potential benefits: economical and social such as creating new jobs, possible to grow profitably as future economics, and perception and attitude of farmers

Positive factors in these criteria according to the literature are being locally abundant; having comparable thermal, acoustical, and physical performance with other contemporary building insulations; having an environmentally friendly production process; requiring less or inexpensive infrastructure; and meanwhile having social and economical benefits for the local society. Apparently negative factors indicate lack of these characteristics.

Assessing these items after choosing the agricultural residue will give a conservative basis in the competitive market. This evaluation is important before any decision at the first stage, because knowing some issues changes everything; for example, soybean and cotton residues are not good options because either not enough of these remain in the field or that which remain decompose rapidly. So some options will be removed from the list at first.

## Conclusions and Further Outlook

This chapter has set out essential information to enable assessment of the potential for agricultural crop residues to be utilized in the manufacture of different building insulations. The discussion has touched on processes for transitioning to a more sustainable way of developing the built environment, availability of the raw materials needed for manufacture, the range of stakeholders with an interest in the materials used to insulate buildings, and in the technical and environmental performances of different agricultural by-products with the potential to be turned into insulation. Globally, construction is one of the largest industries, and so changes made to enhance its performance can translate into significant benefits for society more widely. It would seem that all people would have a stake in a more sustainable construction industry.

Following an extensive review of technical studies, the wealth of information available for most of the products in the areas of thermal and acoustical behavior has been summarised. The same cannot be said for other technical characteristics of agricultural by-products having the potential to be utilized for building insulation. Some 27 agro-waste products were considered in this chapter, and only 5 (corn, coconut, flax, hemp, and jute) were found to have been studied across all 4 categories. The reason for this may have to do with their availability in different climatic situations. Materials that have low thermal conductivity because of porous and foam like structure often also have high sound absorption coefficients. Provided they also have other required properties they may be ideal candidates for use in building construction projects. However, the absence of such information is sure to limit their uptake by suppliers, specifiers, and consumers.

There are only a small number of complete life cycle environmental assessments of different agricultural waste products as building materials. The focus of mechanical and physical tests is on flexibility and strength and water or vapor absorption and permeability; however, these results are not sufficient to prove mechanical and physical viability of these materials.

Currently, extensive commercial networks drive the supply and consumption of conventional synthetic insulation materials deriving from petrochemicals. These networks influence price structures, manipulate information flows, and engage in marketing practices designed to maintain and grow their market share, including encouraging skepticism toward new sustainable solutions. It is therefore important to promote a powerful commercial network for ecological insulations, capable of competing in the same conditions with traditional insulations.

While a range of potential benefits have been discussed, it is likely that there are more that can also be considered when evaluating agricultural by-products for recycling. These include health benefits, natural degradation, transportation requirements, and aesthetic. It could also be useful to understand how new tools such as CIS mapping could be utilized to help ensure consistent supplies of crop residues. These matters will be the subject of future research. There is a huge capacity, latent qualities, and possibilities to turn these residues and develop them into something valuable in the future.

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