Agro-industrial wastes as building insulation materials: a review and challenges for Euro-Mediterranean countries

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Abstract

This study investigates the possibility of using agro-industrial wastes for building products, mainly focusing on their insulation properties. A classification of bio-wastes is provided, namely of the lignocellulosic ones and their features and properties are described. Information about three main topics is collected: world production and consumption of some crops already used as building materials, their chemical composition and their most studied properties. Since the considered materials are lignocellulosic and they have many common features, a comparison is made. The aim is to have comparable information to support future research related to the production of eco-efficient indoor insulation boards. The result of this research is the choice of four different agro-industrial wastes produced in the Euro-Mediterranean Countries. This area was chosen as buildings typically have little or no insulation due to the regional mild climate; however, particularly with climate change, indoor hygrothermal comfort is poor. The collection of information allows some conclusions to be reached about the different bio-wastes already studied and identify gaps in the literature.

Keywords: Bio-wastes; Boards; Fibres; Insulation; Natural materials; Thermal properties.

1. Introduction

The increasing interest in environmental impact and safeguarding of natural resources leads research to find out solutions to reduce the negative effects of human practices. The building sector has been identified as having a significant impact in terms of its ecological consequences. Often it requires high energy inputs, produces high volumes of environmentally harmful wastes and consumes a huge percentage of global water and resources (Chikhi et al., 2013; Asdrubali et al., 2015; Ratiarisoa et al., 2016; Viel et al., 2019). Building materials are one of the major factors influencing the overall environmental impact of the construction sector due to their production, transport, use and end of life. To reduce this problem, some strategies have been found out, whilst others are still being implemented: the use of environment-friendly materials, the employment of local materials, the encouragement of circular economy practices, passive building techniques and the development of new techniques such as off-site construction (Hosseini et al., 2018; Jin et al., 2020). Building materials can also influence the working principles of building, both negatively and positively. They can ensure a passive control of indoor hygrothermal conditions influencing both energy demand and comfort, as well as occupants' well-being and health.

Nowadays, research trends focus on the possibility of using natural materials such as fibres in construction products with clear advantages: low environmental impact, less energy demand, low cost, low density, large-scale availability, biodegradability and good insulation and mechanical properties (Mohanty et al., 2005; Dittenber and GangaRao, 2012; Faruk et al., 2012; Berardi and Iannace, 2015; Nguyen et al., 2018a; Sanjay et al., 2018). Several studies evaluated the use of bio-wastes for building products, considering various possible applications, and analysing their different properties. For example, Asdrubali et al. (2015) collected information about natural and recycled materials used for thermal and acoustic insulation. Nunes et al. (2017) reviewed the use of agricultural products in the building sector, reporting their physical and mechanical properties. They also gave information related to bio-based materials used for particleboards' production. Popescu (2017) reported that research interest in using renewable fibres and bio-wastes for panels' production is growing. Posani et al. (2019) addressed the use of some natural materials for insulating historic constructions. Each material exhibits different properties due to its chemical composition, structure and characteristics (e.g. moisture buffering capacity, thermal insulation performance, mechanical behaviour, etc.). Knowing those properties allows suitable choices to be made, to guarantee the required performance of the composites that include them.

As previously mentioned, the production and transport of materials are among the aspects that influence the main environmental impacts of a building. Employing local materials ready-made in their natural form, such as earth, bamboo, reeds, without using synthetic compounds, offers a sustainable solution. Another efficient possibility is the use of bio-wastes. They are continuously produced, and a significant part of those wastes tends to be landfilled. Sometimes they cause environmental problems and negative effects, but they can also be useful resources when employed in construction (Karade, 2010; Raut et al., 2011; Madurwar et al., 2013; Viel et al., 2018; Kazmi et al., 2018). This guarantees an improvement in the disposal of residues, an incitement to recycle and to eco-friendly construction practices. To encourage their use, it is extremely important to propose solutions that secure similar or better performance compared to conventional building materials.

The present article focuses on lignocellulosic materials, considering both fibres and raw materials as they are. Natural fibres are filamentous substances found in animals, plants and minerals. Vegetal ones are composed mainly of cellulose, whereas animal ones are rich in protein (John and Thomas, 2008). Past studies provided different classifications (Mohanty et al., 2005; Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Nguong et al., 2013; Berardi and Iannace, 2015; Sanjay et al., 2018). Figure 1 shows an adaptation of that proposed by Jawaid and Abdul Khalil (2011), considering all types of fibres. As concerns the lignocellulosic fibres, their features depend on several factors, such as location and climate conditions of crop production, plant species and harvesting (Dittenber and GangaRao, 2012).

Figure 1

The present article carries out a general analysis concerning the use of bio-wastes, studied to create several construction products, such as bricks, plasters, adhesives, and particleboards, and it gives a classification of lignocellulosic bio-wastes. It subsequently deals only with agro-industrial bio-wastes already studied as building materials and their properties. It collects information about worldwide production, chemical composition and properties (focusing mainly on thermal performances). As a result of this data collection, production and consumption in Euro-Mediterranean Countries were taken into account to select some bio-wastes to be studied in more detail. As concerns chemical composition and properties, the article focuses on board production to collect useful information for future research.

The results allow an overview of the state of the art, identifying the gaps in the literature and possible new solutions to produce insulation boards for interior use. The outcome is the selection of four bio-wastes, largely produced in Euro-Mediterranean Countries, to consider and study as aggregates for innovative eco-efficient building composites.

2. Lignocellulosic bio-wastes as building materials and products

Among the natural materials that can be used as building materials, bio-wastes can be an effective possibility. As previously anticipated, they are continuously produced, available in large quantities and can be used to produce different composites. Considering the ones already studied for construction products, it is possible to differentiate some types of bio-wastes and make a classification: those derived from forest management, floriculture and use of flowers and shrubs; those derived from agricultural and manufacturing practices and produced by the use of the agro-products and those from the food industry. Their world production and consumption are substantial and increasing over the years (Papadopoulou et al., 2015; Viel et al., 2018). For this reason, they can be a good source for natural composite production. Tables 1, 2 and 3 report some examples of bio-wastes already examined in past studies related to building materials, considering this classification (forest management and floriculture, agricultural practices and agro-industrial processes respectively). Due to the large quantity of studies, only the research works published in the last decade (2010-2020) were considered.

Table 1 - Example of materials derived from forest management and floriculture already studied for building products considering research works published in 2010-2020.

Lignocellulosic bio-wastes	**Designed product**	**Part of waste**	**Description***	**References**
Hortensia (*Hydrangea macrophylla* (Thumb.) Ser)	Polymers	Stem	Dried stems of Hortensia to produce a bio-polymer for thermal insulation materials. Study of samples made up of hortensia and commercial polyurethane.	Cárdenas et al., 2018
	Polymers, binders	Stem	Feasibility of the production of a bio-polymer for thermal insulation materials and a binder for insulation panels production.	Cárdenas, 2020
Cattail (*Typha latifolia* L.)	Boards	Fibre	A past studies that analysed thermal insulation boards composed of Cattail fibres and Methylene Diphenyl Diisocyanate binder.	Asdrubali et al., 2015
Rape straw (*Brassica napus* L.)	Concretes	Straw	Rape straw derived from the woody heart of the stems. Analysis of hygric properties of concrete made of rape straw and lime.	Nguyen et al., 2017; Rahim et al., 2016
	Aggregates	Straw	Characterization of rape straw to evaluate its possible use as a raw building material for different compounds.	Viel et al., 2018
Agave (*Agave* sp.)	Boards	Fibre	Thermal insulation material made of agave fibres/wheat straw and corn starch as a binder.	Ali et al., 2020a
Apple of Sodom (*Calotropis procera* (Aiton) W.T.Aiton)	Boards	Fibre	Boards made up of Apple of Sodom fibres, Phenol-Formaldehyde resin and cornstarch as binders.	Ali and Zeitoun, 2012
	Composites	Fibre	Hybrid insulating composites made up of Apple of Sodom fibre, date palm tree surface fibre and Agave fibre and cornstarch, white cement and glue (wood adhesive 78-1040) as binders.	Alabdulkarem et al., 2018
Lavender (*Lavandula angustifolia* Mill.)	Aggregates	Straw	Analysis of lavender straw as possible bio-aggregate in a pozzolanic matrix composed of metakaolin and slaked lime.	Ratiarisoa et al., 2016
Miscanthus (*Miscanthus* spp.)	Boards	Fibre	Boards made up of Miscanthus fibres, sunflower stalk and natural binders (starch-based binder, wood glue made of casein, bone glue).	Eschenhagen et al., 2019
	Boards	Fibre	Thermal insulation boards made up of Miscanthus fibres, cement-based binder and hydrated lime.	Savic et al., 2020
Reed (*Phragmites australis* (Cav.) Trin ex. Steud.)	Aggregates	Wooden parts, bark	Evaluation of the acoustic properties of the raw material to produce sound-absorbing boards.	Berardi and Iannace, 2015

Cork (*Quercus suber* L.)	Boards	Granules	Sandwich panels with thermal insulation properties having cork as core and commercial flax fibres and epoxy resin as external layers.	Liu et al., 2017; La Rosa et al., 2014
	Aggregates	Granules	Past studies that examined cork for mortar and concrete production (to replace stone).	Chikhi et al., 2013
	Aggregates	Granules	Acoustic properties of the raw material are evaluated to produce sound-absorbing boards.	Berardi and Iannace, 2015
	Concretes	Granules	Cement-bonded composites made of cork granules to produce lightweight concrete.	Karade, 2010
Eucalyptus fibres (*Eucalyptus* spp.)	Composites	Fibre	A past study that investigated the feasibility of using Eucalyptus fibres as reinforcement in cement-based matrices.	Chikhi et al., 2013

* Note: The description section reports "past study/past studies" when the cited articles refer to other past research work.

Table 2 - Example of materials derived from agricultural practices already studied for building products considering research works published in 2010-2020.

Lignocellulosic bio-wastes	**Designed product**	**Part of waste**	**Description***	**References**
Banana (*Musa* spp.)	Composites	Fibre	Past studies that analysed banana fibres and several materials: cement, polyurethane, aliphatic polyester resin, PP, urea-formaldehyde, PE, polyester, polyvinyl alcohol.	Faruk et al., 2012
	Composites	Fibre	Past studies that considered several banana composites such as banana/kenaf and unsaturated polyester, sisal/banana and polyester, banana/glass and phenol-formaldehyde, banana/glass and polypropylene (PP), banana/glass hybrid fibre reinforced polystyrene composite.	Jawaid and Abdul Khalil, 2011
	Composites	Fibre	Past studies that considered banana reinforced composites.	Sanjay et al., 2018
	Mortars	Fibre	Feasibility of using banana fibres for polymer-modified cement mortars (banana fibres could partially replace cement).	Akinyemi and Dai, 2020
	Composites	Fibre	A past study that analysed epoxy composites reinforced by banana fibre.	Nguong et al., 2013
	Boards	Fibre	Feasibility of using banana fibres partially replacing maritime pine (*Pinus pinaster* Ait.) particles for cement-bonded particleboards	Nunes et al., 2021
Cereal (several species)	Plasters	Straw	A past study that evaluated the hygrothermal properties of clay plasters with barley (*Hordeum vulgare*) straw and corn pith.	Liuzzi et al., 2018
	Boards	Straw	A past study that considered fibreboards with barley straw.	Nguyen et al., 2017
	Insulation materials	Straw	Past studies that analysed insulation materials with cereal straws.	Liu et al., 2017
	Composites	Straw	Past studies that considered cereals straw in different applications.	Cárdenas et al., 2018
	Binders	Grains	Cereals grains (corn and wheat) to produce starch used as a binder.	Monteiro et al., 2016

	Boards	Straw	Thermal insulation material made up of agave fibres/wheat straw and corn starch as a binder.	Ali et al., 2020a
	Boards	Straw	Straw used for bio-insulation materials (fibreboards).	Nguyen et al., 2020
	Boards	Straw	Past studies that considered cement-bonded particleboards.	Karade, 2010
Corn (*Zea mays* L.)	Plasters	Pith	A past study that evaluated the hygrothermal properties of clay plasters with barely straw and corn pith.	Liuzzi et al., 2018
	Insulation materials	Straw, stalk	Past studies that analysed insulation materials with corn.	Liu et al., 2017
	Natural glues	Starch	A past study that considered corn to produce wood adhesives for indoor applications.	Cardoso et al., 2015
	Boards	Cob	Past studies that considered particleboards made of ground corn cobs and wood glue.	Asdrubali et al., 2015
	Insulation materials	Cob	A past study that considered corn to produce thermal insulation material.	Chikhi et al., 2013
	Aggregates	Cob	Hemp shiv, corn cob and natural binders to produce thermal insulation materials.	Viel et al., 2019
	Insulation blocks	Husk	Insulation block made of wheat straw and corn husk.	Rojas et al., 2019
	Boards, cement	Husk, cob	Past studies that considered particleboards composed of waste tissue paper manufacturing and corn peel, and cement produced by corn cob ash.	Madurwar et al., 2013
	Insulation materials	Cob	A past study that considered corn cob for bio-insulation materials.	Nguyen et al., 2020
	Boards	Starch	Thermal insulation material composited of agave fibres/wheat straw and corn starch as a binder.	Ali et al., 2020a
Cotton (*Gossypium* spp.)	Boards	Stalk	A past study that considered thermal insulation fibreboard made by a hot-pressing method.	Liu et al., 2017
	Boards	Stalk	A past study that considered particleboards made of cotton stalk manufactured without using chemical binders.	Asdrubali et al., 2015
	Composites	Fibre	Past studies that considered cotton fibres for different applications.	Cárdenas et al., 2018
	Composites	Fibre	Past studies that considered several cotton fibres composites such as jute/cotton and novolac phenolic or polyester, cotton/ramie and polyester, sisal/cotton and polyester.	Jawaid and Abdul Khalil, 2011
	Composites	Fibre	Past studies that analysed cotton-polyester composites.	Shalwan and Yousif, 2013
	Boards, bricks	Stalk, waste	Past studies that considered cotton stalk for fibreboard production without chemical additives and cotton waste for brick production.	Madurwar et al., 2013
	Bricks	Waste	A past study that considered cotton waste and lime powder waste to produce bricks.	Raut et al., 2011
Date palm fibres (*Phoenix dactylifera* L.)	Mortars	Fibre	A past study that evaluated mortars made up of sand, cement and date palm fibres.	Liuzzi et al., 2018
	Insulation materials	Fibre	A past study that evaluated the properties of date palm and gypsum-based materials.	Liu et al., 2017

	Insulation materials	Fibre	A past study that evaluated the properties of date palm and gypsum-based materials.	Asdrubali et al., 2015
	Insulation materials	Fibre	Properties of date palm and gypsum-based materials.	Chikhi et al., 2013
	Insulation materials	Fibre	Evaluation of thermal insulation and mechanical properties of a composite made up of date palm surface fibres and cornstarch solution as a binder.	Ali and Alabdulkarem, 2017
Flax (*Linum usitatissimum* L.)	Composites	Fibre	A past study that considered lime-flax shiv composite.	Nguyen et al., 2017
	Insulation materials	Fibre	Past studies that considered flax fibres for insulation materials.	Liu et al., 2017
	Composites	Fibre	Past studies that analysed flax fibre composites.	Faruk et al., 2012
	Composites	Fibre	Past studies that considered several flax fibres composites such as flax/glass and polypropylene, cotton/flax and polyethylene.	Jawaid and Abdul Khalil, 2011
	Composites	Fibre	Past studies that considered flax fibre reinforced composites.	Sanjay et al., 2018
	Boards	Shiv	A past study that evaluated the properties of fibreboards made up of flax-shiv and casein binder.	Nguyen et al., 2018a
	Aggregates	Shiv	Characterization of rape straw to evaluate the feasibility of using it as a raw building material for different composites.	Viel et al., 2018
	Boards	Shiv	Past studies that considered fibreboards composed of flax fibres without binders, with tannin binder and protein binder.	Nguyen et al., 2020
	Boards	Shiv	Properties of particleboards made up of flax shiv, sunflower stems and urea-formaldehyde as a binder.	Mahieu et al., 2019
Hemp (*Cannabis sativa* L.)	Concrete, Boards	Shiv, Fibre	Past studies that considered hemp concrete properties and fibreboards made up of hemp fibres.	Nguyen et al., 2017
	Insulation materials	Straw, fibre	A past study that evaluated the properties of hemp fibres for insulation materials.	Liu et al., 2017
	Boards	Fibre	Past studies that considered thermal and acoustic insulation properties of boards made of hemp fibre.	Nguyen et al., 2018b
	Aggregates	Shiv	Characterization of hemp shiv to evaluate the feasibility of using it as a raw building material for different composites.	Viel et al., 2019
	Boards	Fibre	Considered acoustic insulation properties of boards produced by treating hemp fibres with materials to improve the fire resistance (soda or boron salts).	Berardi and Iannace, 2015
	Composites	Fibre	Past studies that considered hemp fibres in composites.	Faruk et al., 2012
	Composites	Fibre	Past studies that considered hemp fibre composites such as hemp/glass and polypropylene.	Jawaid and Abdul Khalil, 2011
	Aggregates	Shiv	Characterization of hemp shiv to evaluate the feasibility of using it as a raw building material for different composites.	Viel et al., 2018
	Concretes	Fibre	Past studied that considered bio-concrete.	Nguyen et al., 2020
Kenaf (*Hibiscus cannabinus* L.)	Boards	Fibre	Acoustic insulation properties (sound absorption) of pure kenaf samples.	Berardi and Iannace, 2015
	Composites	Fibre	Past studies that considered kenaf fibres in composites.	Faruk et al., 2012

	Composites	Fibre	Past studies that considered several kenaf fibres composites such as kenaf/glass and natural rubber and banana/kenaf hybrid composites.	Jawaid and Abdul Khalil, 2011
	Composites	Fibre	Past studies that considered fibre-reinforced composites such as kenaf/PP, kenaf/corn starch, kenaf/epoxy.	Shalwan and Yousif, 2013
Rice (*Oryza* spp.)	Boards	Husk	Boards made up of rice husk, earth, gypsum and air lime.	Antunes et al., 2019
	Boards	Husk, straw	A past study that evaluated particleboards composed of rice husk and acoustic properties of rice straw measured in a reverberation room.	Asdrubali et al., 2015
	Composites	Husk, straw	Past studies that analysed rice husk and rice straw composites.	Faruk et al., 2012
	Bricks	Husk, husk ash	Past studies that considered rice husk for brick production.	Ozturk et al., 2019
	Bricks, cement	Husk, straw	Past studies that considered brick made of different compounds: sludge from dried water treatment and rice husk, rice husk ash and expanded polystyrene, clay sand and rice husk ash. A past study that evaluated rice husk as cement replacement material.	Madurwar et al., 2013
	Bricks	Husk	A past study that evaluated clay-sand brick varying percentages of rice husk ash and firing times.	Raut et al., 2011
	Glues	Bran	A past study that considered the adhesive properties of rice bran (composed of starch and protein) to fabricate plywood specimens.	Patel et al., 2013
	Composites	Husk	Properties and manufacturing process of bio-composites made of rice husk.	Muthuraj et al., 2019

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Table 3 - Example of materials derived from agro-industrial processes already studied for building products considering research works published in 2010-2020.

Lignocellulosic bio-wastes	**Designed product**	**Part of waste**	**Description***	**References**
Bagasse/Sugarcane (*Saccharum officinarum* L.)	Boards	Fibre	Past studies that considered thermal conductivity and acoustic properties of bagasse boards.	Asdrubali et al., 2015
	Cement	Fibre, ash	Past studies that examined bagasse as cement reinforced and bagasse ash as cement replacement material.	Madurwar et al., 2013
	Insulation materials	Fibre	A past study that evaluated bagasse fibres properties for thermal insulation materials.	Nguyen et al., 2020
	Boards	Fibre	Past studies that considered particleboards made of bagasse and manufacture process.	Karade, 2010
	Boards	Waste	Analysis of indoor insulation boards without chemical binding additives.	Panyakaew and Fotios, 2011
	Boards	Stalk	Particleboards made of bagasse stalk (cut and dried) and citric acid.	Syamani et al., 2020

Cassava (*Manihot esculenta* Crantz)	Binders	Starch	Sour cassava starch, distilled water, chitosan solution, *Populus* fibres and glycerol as binders for particleboards production.	Monteiro et al., 2016
	Binders	Starch	Sour cassava starch, distilled water, chitosan solution, *Pinus pinaster* fibres and glycerol as binders for particleboards production.	Monteiro et al., 2019
Citrus (*Citrus* spp.)	Binders and additives	Citric acid	Review that reported properties of citric acid as a binder and additive to modify wood properties.	Lee et al., 2020
	Binders	Citric acid	Citric acid dissolved in water and used as adhesive for particleboards production.	Widyorini et al., 2016
	Boards	Citric acid	Particleboards made of bagasse stalk (cut and dried) and citric acid (dissolved in water).	Syamani et al., 2020
Coconut (*Cocos nucifera* L.)	Composites	Fibre	Past studies related to the possibility of replacing synthetic fibres in composites.	Liuzzi et al., 2018
	Boards	Fibre	A past study that demonstrated the feasibility of using coconut fibres for board production.	Ashour et al., 2010
	Boards	Fibre	Acoustic insulation properties of coconut brown fibres.	Berardi and Iannace, 2015
	Composites	Fibre	Past studies that considered fibre-reinforced composites such as coir/PP, coir/polyester.	Shalwan and Yousif, 2013
	Boards	Fibre, pith	A past study that analysed particleboards made of durian peel and coconut coir	Madurwar et al., 2013
	Boards	Fibre	A past study that provided some recommendation to produce cement-bonded boards and their properties.	Karade, 2010
	Boards	Husk (fibre and pith)	Analysis of indoor insulation boards without chemical binding additives.	Panyakaew and Fotios, 2011
Coffee (*Coffea* spp.)	Boards	Chaff	Acoustic properties of samples made of coffee chaff and polyurethane glue.	Ricciardi et al., 2017
	Geo-polymers	Ground	New polymer composed of coffee grounds, blast furnace slag and fly ash.	Kua et al., 2016
	Bricks	Ground	Brick made of clay and coffee ground, compressed, dried and fired.	Eliche-Quesada et al., 2011
	Plasters	Ground	Analysis of a plaster made of semi hydrate gypsum and different percentages of coffee grounds.	Lachheb et al., 2019
	Bricks	Ground	Fired clay bricks with coffee grounds.	Muñoz Velasco et al., 2016
Durian (*Durio* spp.)	Boards	Peel	A past study that evaluated particleboards composed of durian peel and different type of binders.	Asdrubali et al., 2015
	Boards	Peel	A past study that analysed particleboards made of durian peel and coconut coir.	Madurwar et al., 2013
Hazelnut (*Corylus avellana* L.)	Cement	Shell	A past study that evaluated the properties of cementitious composite with hazelnut shells.	Karade, 2010
	Polymers	Shell	Modified polymer (HDPE) using hazelnut shells.	Salasinska and Ryszkowska, 2012

	Boards	Shell	Feasibility of replacing wood particles with hazelnut shells for particleboard production using resin and hot pressing method.	Lopes et al., 2012
Jute (*Corchorus* spp.)	Composites	Fibre	Past studies that considered jute fibres composites such as jute/glass and polypropylene.	Jawaid and Abdul Khalil, 2011
	Composites	Fibre	Past studies that considered fibre-reinforced composites such as jute/polylactic acid, jute/polyester.	Shalwan and Yousif, 2013
	Insulation materials	Fibre	A past study that evaluated jute fibres properties for thermal insulation materials.	Nguyen et al., 2020
Olive (*Olea europaea* L.)	Plasters	Fibre	Analysis of clay plasters with olive fibres.	Liuzzi et al., 2018
	Mortars	Stone	Viability of replacing clay with olive stones for lightweight expanded clay mortars.	del Río Merino et al., 2017
	Bricks	Pomace	A past study that evaluated the effect of adding olive pomace in porous bricks.	Ozturk et al., 2019
	Bricks	Husk	A past study that evaluated thermo-mechanical properties of clay bricks with unburnt olive husk.	Madurwar et al., 2013
	Boards	Fibre	Boards made of sodium silicate, olive waste and barely straw.	Liuzzi et al., 2020
	Ceramic materials	Pomace	A past study that evaluated the thermal properties of ceramic materials with olives waste.	Eliche-Quesada et al., 2011
Grape (Vitis spp.)	Glues	Pomace	Feasibility of extracting tannins from wine production waste to produce a natural glue.	Cardoso et al., 2015
	Bricks	Pomace	Fried clay bricks with different percentages of dried wine waste.	Taurino et al., 2019
	Boards	Waste	Particleboards made up of softwood chip, grapevine chip and melamine modified urea-formaldehyde (MUF).	Wong et al., 2020
Soy (*Glycine max* (L.) Merr.)	Glues	Seed	Past studies that considered soy flour as natural glue for wood.	Cardoso et al., 2015
	Glues	Seed	Past studies that used soy protein resin.	Dittenber and GangaRao, 2012
	Binders	Protein	Past studies that demonstrated soy protein adhesive properties.	Monteiro et al., 2016
Sunflowers (*Helianthus annuus* L.)	Glues	Seed	Past studies that considered fibreboards composed of natural fibres and bio-glues (kraft lignin and soybean protein).	Nguyen et al., 2017
	Boards	Piths	A past study that evaluated properties of particleboards made of sunflowers pith with different density and grain size.	Asdrubali et al., 2015
	Boards	Plant	Particleboards realized by a cake produced by drying sunflowers and thermo-pressing.	Evon et al., 2012
	Boards	Stalk	Boards made up of miscanthus fibres, sunflower stalk and natural binders (starch-based binder, wood glue made of casein, bone glue).	Eschenhagen et al., 2019
	Boards	Stem	Properties of particleboards made of flax shiv, sunflower stems and urea-formaldehyde as a binder.	Mahieu et al., 2019

Tea (*Camellia sinensis* L. Kuntze)	Bricks	Waste	A past study that evaluated clay brick with tea waste.	Eliche-Quesada et al., 2011
	Bricks	Waste	Past studies that considered the feasibility of adding tea waste in clay-based bricks.	Ozturk et al., 2019
	Plasters	Plant	Plaster made of hemihydrate gypsums and black tea powder.	Huang et al., 2019
	Bricks	Waste	Properties of bricks with 5% of waste tea (by weight), dried and fired.	Raut et al., 2011

*Note: The description section reports "past study/past studies" when the cited articles refer to other past research work.

3. Bio-wastes derived from forest management and floriculture

Several past research analysed the use of bio-wastes derived from forest management and floriculture. Cárdenas et al. (2018) studied the possibility of using stems of Hortensia (*Hydrangea macrophylla*) to produce thermal insulation materials. The researchers investigated the physical and chemical properties of this plant and studied a composite material adding commercial polyurethane. The results demonstrated that it has good insulation properties and better performances if compared with commercial expanded polystyrene. Asdrubali et al. (2015) considered many past studies that demonstrated the possibility of using residues from forest pruning to produce thermal insulation boards. They reported that particleboards made up of cattail fibre (*Typha*), a plant characterized by very fast growth and that produces negative effects on the other crops, have good performances due to the low thermal conductivity (between 0.044 W/(m.K) and 0.061 W/(m.K)). Ratiarisoa et al. (2016) studied the possibility of using lavender (*Lavandula* sp.) straw, derived from a distillation treatment used in essential oil extraction, to produce a composite. They investigated the physical properties and thermal, mechanical and hygroscopic behaviour of a composite with a pozzolanic binder, made up of Metakaolin and slaked lime. Results showed promising hygrothermal characteristics (thermal conductivity, moisture buffering capacity and water vapour permeability) if compared with other bio aggregates already studied. Viel et al. (2018) considered different bio-based aggregates, including rape straw, derived from *Brassica.* They investigated its chemical and physical characterization and demonstrated that it has good hygrothermal properties, low thermal conductivity, and high moisture buffer value and water absorption. Water absorption results indicated a high porosity, an important feature for thermal insulation performances. Indeed, there is a relationship of inverse proportionality between thermal conductivity and open porosity. Moisture buffer value showed the potential of a material to passively control indoor conditions. The researchers concluded that bio-based aggregates could be used to produce insulation products such as indoor boards. Other past studies (Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Sanjay et al., 2018) have reported that sisal fibres, extracted from *Agave,* are another efficient possibility to produce composites for building.

4. Bio-wastes derived from agricultural practices and agro-industrial processes

Taking into consideration the classification provided in Section 2 (Tables 1, 2 and 3), this study considers in detail only the bio-wastes derived from agriculture practices and agro-industrial processes used to produce building products. It does not carry out a detailed study of bio-wastes deriving from forest cleaning and floriculture. Past research and results are reported below.

4.1 Bio-wastes derived from agricultural practices

Agriculture generates a large number of bio-wastes to ensure crop growth or harvesting, which are often unused, but they can be an important resource for construction. Past research demonstrated the possibility of using these bio-wastes for several applications, considering both raw materials and composites. There are several types of building products made up of residues of agriculture practices. As examples of the application of the raw materials, D'Alessandro et al. (2017) investigated the thermal and acoustic behaviour of a straw bale wall, carrying out laboratory tests and *in situ* analysis. Experimental results demonstrated good thermal performances: thermal conductivity values of the samples with a density of 80 kg/m^3 were between 0.050 W/(m.K) and 0.060 W/(m.K), thus lower than the maximum recommended for thermal insulators, i.e. 0.065 W/(m.K) (AFNOR, 1983). *In situ* measurements demonstrated that straw walls work well in winter conditions but not in summer, due to the high diffusivity and low thermal inertia. In terms of acoustic behaviour, this bio-waste wall did not show great performance, due to lack of mass. Madurwar et al. (2013), Asdrubali et al. (2015) and Liu et al. (2017) reported studies that evaluated thermal behaviour of boards comprising cotton stalk as the fibre component without adding any chemical binders. They had good thermal performance, resulting from a low thermal conductivity. Regarding the use of bio-wastes to produce cement mortars, Akinyemi and Dai (2020) considered treated banana fibres, wood ash and styrene-butadiene polymer. The researchers evaluated mechanical and thermal properties demonstrating that the composite could be used to produce cement elements. Collet and Pretot (2014) analysed the thermal properties of hemp concrete mixing hemp shiv and hydraulic lime. They concluded that thermal performances varied due to the formulation, density and water content. Nunes et al. (2021) studied the properties of cement-bonded particleboards produced by replacing maritime pine particles with banana pseudostem. The researchers observed that increasing the banana fibres (from 0 to 75%) led to higher bulk density (from 1754 kg/m^3 to 1995 kg/m^3) and thermal conductivity (from 0.233 W/(m.K) to 0.279 W/(m.K)).

4.2 Bio-wastes derived from agro-industrial processes

Another source of bio-waste is the use of agricultural products in industrial processes and their consumption. Several studies investigated their properties, encouraging their reuse. For example, Huang et al. (2019) investigated the performances of a composite of tea waste powder and hemihydrate gypsum to produce plastering paste. The tea waste addition determined higher density and longer setting times. Density increased from 2.14 g/cm³ (for the control sample, with no tea waste) to 2.69 g/cm³ by adding 2.5% in mass of tea waste. Initial and final setting times increased from 15 min and 22 min (control sample) to 840 min and 3500 min (sample with 2.5% in mass of tea waste), respectively. Furthermore, Huang et al. (2019) reported that tea waste acted as a water-reducing agent: to obtain the normal consistency of gypsum paste, the water requirement decreased by increasing tea waste content. Different results were obtained by Ozturk et al. (2019), in their evaluation of the properties of tea wastes for the production of fired clay brick. The increase of waste content by 12.5% by weight determined high porosity (up to 56.5%) and water absorption (from 15.9% to 35.3%) of the brick samples. Furthermore, the addition of 12.5% of tea waste reduced bulk density (from 1.79 g/cm³ to 1.38 g/cm³ at 950 °C firing temperature and from 1.88 g/cm³ to 1.41 g/cm³ at 1050 °C) and thermal conductivity (up to 42%) and guaranteed sufficient compressive strength, considering that required for bricks, i.e. 7 MPa (CEN, 2011). Liuzzi et al. (2018) assessed clay-based plaster with different percentages of olive pruning waste fibres (from 4% to 12% by the total weight). They verified that increasing fibre content resulted in a lower density (from 1669 kg/m³ to 1409 kg/m³) and thermal conductivity (from 0.593 W/(m.K) to 0.428 W/(m.K)) and higher porosity. Hence, adding this natural waste improved thermal insulation performance. Past research also considered the use of coffee grounds to produce different building materials. Muñoz Velasco et al. (2016) used this bio-waste as aggregates to produce fired clay brick. They demonstrated that it improved thermal performances since thermal conductivity reduced from 0.73 W/(m.K) (for bricks without coffee grounds) to 0.38 W/(m.K).

4.3 World production and consumption

Production and transport of building materials entail energy wastes and environmental impacts. Choosing local products reduces this problem, enhancing the characteristic of the considered area. This is the primary aim of using bio-wastes for building products. World production, major producers and major consumers are useful information to make sustainable choices. Depending on the country or region, a specific bio-waste can be selected and used.

Table 4 shows the ranking of the production in 2019 of agricultural products already studied for building products in decreasing order of world production volume and five major producing countries according to FAOSTAT (FAO, 2020a). Table 4 also reports data provided by Atlas Big (2020) as an additional source of information. The production from Euro-Mediterranean Countries is highlighted in grey shade.

Table 4 – World production of agricultural products in 2019 (adapted from FAO (2020a) and Atlas Big (2020).

		FAOSTAT (2020)			**Atlas Big (2020)**
Material	**World production [x 10^5 tonnes]**	**Five major producers and production [x 10^5 tonnes]**		**Land used - Country area [1000ha]**	**World production per year [x 10^5 tonnes]**
Sugar cane	19498.85	Brazil	7528.95	851577.00	18892.69
		India	4054.16	328725.90	
		Thailand	1310.02	51312.00	
		China	1099.63	960001.29	
		Pakistan	668.80	79610.00	
Maize	11571.05	United States of America	3470.48	983151.00	10602.48
		China	2609.58	960001.29	
		Brazil	1011.39	851577.00	
		Argentina	568.61	278040.00	
		Ukraine*	358.80	60355.00	
Wheat (*Triticum* spp.)	7657.74	China	1336.01	960001.29	7494.68
		India	1035.96	328725.90	
		Russian Federation	744.53	1709825.00	
		United States of America	522.58	983151.00	
		France	406.05	54908.70	
Rice	5050.96	China	1410.07	960001.29	7425.42
		India	1184.89	328725.90	
		Indonesia	364.21	191686.22	
		Bangladesh	364.09	14757.00	
		Viet Nam	289.80	33123.00	
Palm oil (*Elaeis* spp).	4106.97	Indonesia	2456.33	191686.22	588.00
		Malaysia	990.65	33034.50	
		Thailand	167.72	51312.00	
		Nigeria	100.25	92377.00	
		Colombia	83.90	114175.00	
Banana	1171.23	India	304.60	328725.90	1132.12
		China	119.98	960001.29	
		Indonesia	72.81	191686.22	
		Brazil	68.13	851577.00	
		Ecuador	65.83	25637.00	
Seed cotton	825.89	China	235.05	960001.29	261.73

		India	185.50	328725.90	
		United States of America	129.56	983151.00	
		Brazil	68.93	851577.00	
		Pakistan	44.95	79610.00	
Grapes	770.62	China	143.72	960001.29	775.18
		Italy	79.00	30207.00	
		United States of America	62.33	983151.00	
		Spain	57.45	50595.73	
		France	54.90	54908.70	
Coconut	624.74	Indonesia	171.29	191686.22	583.53
		Philippines	147.65	30000.00	
		India	146.82	328725.90	
		Sri Lanka	24.69	6561.00	
		Brazil	23.31	851577.00	
Sunflower seed	560.73	Russian Federation	153.79	1709825.00	473.47
		Ukraine	152.54	60355.00	
		Argentina	38.26	278040.00	
		Romania	35.69	23840.00	
		China	24.20	960001.29	
Pineapples *Ananas comosus* (L.) Merr.	286.10	Costa Rica	33.28	5110.00	262.90
		Philippines	27.48	30000.00	
		Brazil	24.27	851577.00	
		Indonesia	21.96	191686.22	
		China	21.59	960001.29	
Olives	194.67	Spain	59.65	50595.73	192.70
		Italy	21.94	30207.00	
		Morocco	19.12	44655.00	
		Turkey	15.25	78535.00	
		Greece	12.28	13196.00	
Coffee	100.36	Brazil	30.09	851577.00	92.18
		Viet Nam	16.84	33123.00	
		Colombia	8.85	114175.00	
		Indonesia	7.61	191686.22	
		Ethiopia	4.83	113625.94	
Tea	65.12	China	27.92	960001.29	59.66
		India	13.90	328725.90	
		Kenya	4.59	58037.00	
		Sri Lanka	3.00	6561.00	
		Viet Nam	2.69	33123.00	
Jute *Corchorus* spp.)	33.76	India	17.09	328725.90	33.92
		Bangladesh	16.00	14757.00	
		China	0.30	960001.29	
		Uzbekistan	0.15	44892.40	
		Nepal	0.11	14718.00	
Hazelnuts	11.25	Turkey	7.76	78535.00	7.43
		Italy	0.99	30207.00	
		Azerbaijan	0.54	8660.00	
		United States of America	0.40	983151.00	
		Chile	0.35	75670.00	
Flax	10.86	France	8.50	54908.70	8.73
		Belgium	0.94	3053.00	

		Belarus	0.46	20760.00	
		Russian Federation	0.38	1709825.00	
		China	0.18	960001.29	
Sisal *(Agave sisalana* Perrine ex Engelmann)	2.07	Brazil	0.87		2.81
		United Republic of Tanzania	0.33	94730.00	
		Kenya	0.21	58037.00	
		Madagascar	0.18	58729.50	
		Haiti	0.14	2775.00	
Hemp	1.74	France	0.78	54908.70	-
		Democratic People's Republic of Korea	0.15	12054.00	
		China	0.15	960001.29	
		Netherlands	0.14	4154.00	
		Poland	0.14	31269.00	

Note: No data is presented when it is not provided by the considered reference.

The three major agricultural products are sugar cane, maize and wheat. Considering only the Euro-Mediterranean Countries, Italy is one of the largest producers of grapes, hazelnuts and olives. Spain is the world's largest producer of olives and the fifth largest producer of grapes. Greece is among the fifth largest producers of olives. France is a major producer of flax, hemp and among the main producers of wheat and grapes. These productions and countries are marked in grey in Table 4.

For the region considered in this article, consumption and use are hereby assessed in more detail. According to FAOSTAT (FAO, 2020b), Spain, Italy and Greece are the three major producers of olive oil and olives, hence great producers of olives residues; Portugal is among the top ten world producers. Italy, Spain and France are the three major producers of wine and therefore the major grape users; Portugal and Greece are among the first fifteen countries. According to INC Statistical Yearbook (INC, 2020), Italy is not only one of the largest producers but also the top consumer of hazelnut in the world. In addition, world consumption is increasing every year. The International Coffee Organization (ICO, 2020) gives information about coffee consumption by importing countries in 2013, the last year for which there is a large amount of comparable information. France, Italy and Spain are some of the major consumers. Therefore, coffee bio-wastes derived from its use are considered rather than its industrial production (coffee grounds).

These results allow choosing for further research four agricultural products as important sources of bio-waste in Euro-Mediterranean Countries: grapes, olives and hazelnuts due to their production and coffee because of its consumption. Using them guarantees a sustainable practice ensuring a reduction in costs and consumption derived from production and transport.

4.4 Chemical composition

Agro-industrial wastes considered in this work are vegetal products. Even if they have different origins, they have similar characteristics such as chemical composition. Cellulose, hemicelluloses and lignin are the main structural components of vegetal fibres and agro-products (Summerscales et al., 2010; Faruk et al., 2012; Pedras et al., 2020), with other natural substances, such as extractives, pectin, waxy substances like suberin or cutin and ash. Suberin is present in most wood barks and mainly in cork-rich barks such as *Quercus suber* L., *Q. cerris* L.or *Pseudotsuga menziesii* (Mirb.) Franco (Graça and Pereira, 1999; Lopes et al., 2000; Esteves et al., 2017; Sen et al., 2020). Cutin is the major component of the cuticle, a hydrophobic layer that covers the aerial epidermis of all land plants, providing protection against desiccation and external environmental stresses (Yeats and Rose, 2013). Each of the components plays a specific role. They vary depending on the plant and are different in the distinct parts of the same plant. The components depend on several factors: the plant and its age, the location and climatic context, the soil conditions, harvesting, the extraction and the degradation process (Jawaid and Abdul Khalil, 2011).

Cellulose is a linear homopolymer that can be represented by $[C_6(H_2O)_5]_n$, where n represents the degree of polymerization that can reach 10 000 or higher (Pan, 2011). It has a partially crystalline structure that guarantees hydrophobic behaviour (Mohanty et al., 2005; John and Thomas, 2008; Jawaid and Abdul Khalil, 2011; Summerscales et al., 2010). It is an insoluble polysaccharide composed of fermentable sugar and is formed by repeating units of β-D-glucopyranose linked, by glycosidic bonds. For this reason, glucose is the product of its degradation (Singh Nee Nigam and Pandey, 2009; Nguyen et al., 2017; Echeverria and Nuti, 2017). Cellulose is present in large quantities on earth and it is the main component of the vegetable cell walls, providing structural support to them. Pre-treatments to prepare cellulose are normally costly and harmful (John and Thomas, 2008; Summerscales et al., 2010; Mikkonen and Tenkanen, 2012; Madurwar et al., 2013; Lei and Feng, 2020).

Hemicellulose is the second most widespread group of polysaccharides on earth (Ramos et al., 2017). Hemicelluloses are made up of different types of fermentable sugars: copolymers of glucose, glucuronic acid, mannose, arabinose, galactose and xylose, cross-linked with cellulose with hydrogen bonds (Yang et al., 2007; Summerscales et al., 2010; Ramage et al., 2017). Hemicelluloses have an amorphous linear structure with a lower degree of polymerization than cellulose. They are major constituents in plants and are extremely important in their structure, acting as a filler for the cellular network connecting cellulose and lignin (Singh Nee Nigam and Pandey, 2009; Mikkonen and Tenkanen, 2012; Ramos et al., 2017).

Lignin is a three-dimensional, aromatic polymer consisting of phenylpropane units, joined together, by carbon-carbon and carbon-oxygen-carbon bridging bonds (Mahmood et al., 2016). Its formula can be represented by $[C_{10}H_{12}O_3]_n$ (Pan, 2011). It is amorphous and it has a complex structure composed of three different monomers derived from *p*-coumaryl, coniferyl, and sinapyl alcohols (Lourenço et al., 2016). It is not soluble in several solvents and it cannot be divided into monomeric units. Comparing with cellulose and hemicelluloses, it is the most complex compound to decompose. There is still not an exact method to isolate lignin in its native state from the fibre (John and Thomas, 2008; Nguyen et al., 2017). It provides rigidity to the cell walls of plants and works as structural support, even if cellulose plays a more important role in this task (John and Thomas, 2008; Jawaid and Abdul Khalil, 2011; Dittenber and GangaRao, 2012). It provides covalent linking into the cell wall, ensuring mechanical strength to the cell wall and therefore to the whole plant. It has good resistance to water and microorganism attack (Singh Nee Nigam and Pandey, 2009).

Table 5 provides information about the percentages of the main macromolecular compounds in lignocellulosic materials; cellulose, hemicelluloses, lignin and waxes but also ash content for agricultural products analysed in past research and considered earlier (Table 4). Since each of those components determines different properties in building elements, knowing the chemical composition allows important considerations to be made. A significant amount of research has been published in this field but this review has considered and reported only past studies published between 2000-2020. Poletto et al. (2014) analysed natural fibres and reported that chemical composition influences their physical and mechanical features. Larger quantities of hemicelluloses cause higher moisture absorption and desorption, granting a higher moisture buffering capacity (Cascione et al 2019) and degradation at lower temperatures. Fibres with high percentages of crystalline cellulose have higher thermal stability and tensile properties. This also influences water absorption, as indicated by Cabral et al. (2018). Panyakaew and Fotios (2011) reported that lignin can be used as a natural resin to produce particleboards and that cellulose fibres can give higher stability when used as a filler in composites. Zhou et al. (2010) indicated that lignin and cellulose are the two major compounds used to manufacture binderless fibreboards, thus avoiding the use of synthetic binders such as formaldehyde-based resins that are considered as a potentially harmful solution due to volatile organic compounds released in service. Hot pressing treatment secures this result, but it also produces boards with high densities, not optimal for thermal insulation, although with higher mechanical properties. Cardoso et al. (2015) considered lignin as an attractive material to produce natural glues for wood; however, they say that it is difficult to reach efficient results if compared with conventional binders. Hemmilä et al. (2017) described the viability of using lignin to produce adhesive materials, reporting several examples. Younesi-Kordkheili and Pizzi (2020) used lignin as an additive to obtain a natural wood adhesive, demonstrating the feasibility of using it for panel production. Owodunni et al. (2020a) studied the possibility of producing coconut particleboards using natural binders and concluded that high content of lignin enhanced the bonding process. Improving the understanding of the relationship between properties and cellulose, hemicelluloses and lignin content is an interesting topic for future research. A more detailed version of Table 5 is given as supplementary material.

Table 5 – Chemical composition of several bio-wastes considering research works published in the last twenty years (2000-2020).

Material	**Chemical composition [%]**					**References**
	Cellulose	**Hemicelluloses**	**Lignin**	**Waxes**	**Ash**	
Banana (range)	60.00-65.00	10.00-19.00	5.00-10.00	-	-	(Idicula et al., 2006; Jawaid and Abdul Khalil, 2011; Dittenber and GangaRao, 2012; Nguong et al., 2013)
Coconut fibres/coir (range)	21.00-64.00	0.15-67.63	19.40-47.00	-	0.74	(Khedari et al., 2004; Phan et al., 2006; Jawaid and Abdul Khalil, 2011; Panyakaew and Fotios, 2011; Faruk et al., 2012;; Dittenber and GangaRao, 2012; Nascimento et al., 2016; García et al., 2016; Laborel-Préneron et al., 2016)
Coffee chaff (range)	13.00-24.00	11.00-19.30	17.80-32.00	-	5.94-6.90	(Zarrinbakhsh et al., 2016; Buratti et al., 2018; Quosai et al., 2018)
Coffee grounds (range)	8.60-52.42	6.80-44.50	18.30-24.52	-	0.98-2.52	(Muñoz Velasco et al., 2016; Zarrinbakhsh et al., 2016; Buratti et al., 2018; Ribeiro et al., 2018; Lachheb et al., 2019; Pedras et al., 2019)
Corn cobs/Maize (range)	33.70-48.10	31.90-44.40	3.30-30.30	-	0.46-2.88	(García et al., 2016; Viel et al., 2018; Viel et al., 2019; Cárdenas, 2020)
Corn cob/ Maize residues	27.10	13.87	0.64	-	0.43	(Viel et al., 2019)
Corn/Maize stalks	35.00-39.60	16.80-35.00	7.00-18.40	-	-	(Cárdenas, 2020)
Corn stover	47.40	30.30	22.30	-	-	(García et al., 2016)

Cotton (range)	58.48-90.00	5.70-42.50	2.00-21.45	0.60	5.54	(Jawaid and Abdul Khalil, 2011; Pirayesh and Khazaeian, 2012; Dittenber and GangaRao, 2012; Nguong et al., 2013; García et al., 2016; Cárdenas, 2020)
Cotton stalk (range)	32.00-66.20	18.40-28.00	15.40-26.00	-	8.16	(García et al., 2016; Nguyen et al., 2017)
Flax (range)	28.51-81.00	13.00-27.00	2.00-31.20	1.50-1.70	1.48-4.20	(Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Dittenber and GangaRao, 2012; Nguong et al., 2013; Papadopoulou et al., 2015; García et al., 2016; Laborel-Préneron et al., 2016; Viel et al., 2018; Viel et al., 2019; Cárdenas, 2020)
Flax fine	28.51	15.80	18.14	-	4.20	(Viel et al., 2018)
Flax fine residues	16.21	5.83	7.74	-	2.92	(Viel et al., 2019)
Grapes waste pomace (range)	15.00-50.16	6.62-11.30	30.30	-	3.70-7.00	(Barbieri et al., 2013; Muñoz et al., 2014; Pedras et al., 2020)
Hazelnuts (range)	55.10	34.50-34.60	35.10-41.40	-	8.22-8.23	(Çöpür et al., 2007; Pirayesh and Khazaeian, 2012)
Hazelnut shells (range)	22.90-34.60	11.30-23.50	30.20-41.40	-	1.40-8.22	(Çöpür et al., 2007; Guler et al., 2008; Lopes et al., 2012; Salasinska and Ryszkowska, 2012; Licursi et al., 2017)
Hemp (range)	44.00-78.30	5.50-22.40	2.90-28.00	0.80	0.67-8.80	(Summerscales et al., 2010; Jawaid and Abdul Khalil, 2011; Dittenber and GangaRao, 2012; Shalwan and Yousif, 2013; Nguong et al., 2013; Papadopoulou et al., 2015; Laborel-Préneron et al., 2016; Viel et al., 2018)
Jute (range)	33.40-72.00	12.00-22.70	11.80-28.00	0.50	0.62	(Phan et al., 2006; Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Dittenber and GangaRao, 2012; Madurwar et al., 2013; Nguong et al., 2013; Laborel-Préneron et al., 2016)
Kenaf (range)	31.00-72.00	3.00-33.90	8.00-21.20	-	4.00	(Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Dittenber and GangaRao, 2012; Nguong et al., 2013;

						Papadopoulou et al., 2015; Laborel-Préneron et al., 2016)
Palm oil (range)	49.00-65.00	21.00	11.00-29.00	-	2.00	(Jawaid and Abdul Khalil, 2011; Dittenber and GangaRao, 2012; Laborel-Préneron et al., 2016)
Palm oil frond	56.03	27.51	20.48	-	2.40	(Jawaid and Abdul Khalil, 2011)
Olive husks	25.00	24.60	50.40	-	14.21	(García et al., 2016; Christoforou et al., 2017)
Olive whole stones	31.90	21.90	26.50	-	-	(Fernández-Bolaños et al., 1999)
Olive seed husks	36.40	26.80	26.00	-	-	(Fernández-Bolaños et al., 1999)
Olive pomace	-	-	-	-	3.20-8.63	(Christoforou et al., 2017)
Pineapples	81.00	-	12.70	-	-	(Idicula et al., 2006)
Ramie (range)	68.60-85.00	13.00-16.70	0.50-0.70	0.30	-	(Jawaid and Abdul Khalil, 2011; Faruk et al., 2012; Dittenber and GangaRao, 2012)
Rice husk (range)	30.00-45.00	19.00-25.00	20.00-33.00	14.00-17.00	14.00	(Faruk et al., 2012; Brás et al., 2019)
Rice straw (range)	36.20-57.00	19.00-33.00	8.00-24.00	8.00-38.00	-	(Faruk et al., 2012; García et al., 2016; Cárdenas, 2020)
Sisal (range)	38.20-78.00	10.00-26.00	8.00-26.00	2.00	-	(Idicula et al., 2006; Jawaid and Abdul Khalil, 2011; Dittenber and GangaRao, 2012; Faruk et al., 2012; Madurwar et al., 2013; Nguong et al., 2013; Laborel-Préneron et al., 2016)
Sugar cane/bagasse (range)	32.00-55.20	16.80-37.50	10.00-25.30	-	-	(Faruk et al., 2012; Dittenber and GangaRao, 2012; García et al., 2016; Cárdenas, 2020)
Sunflower seed	24.10	28.60	29.40	-	-	(Cárdenas, 2020)
Sunflower stalks	42.10	29.66	13.44	-	-	(Cárdenas, 2020)

Sunflower whole plant	23.93	7.83	9.13	-	-	(Evon et al., 2012)
Sunflower shells	66.20	18.40	15.40	-	-	(García et al., 2016)
Tea residue	33.30	23.20	43.50	-	-	(García et al., 2016)
Vine shoots	41.14	26.00	20.27	-	-	(Cárdenas, 2020)
Wheat straw (range)	32.90-50.00	15.00-35.50	5.24-20.00	-	0.82-5.90	(Karade, 2010; Faruk et al., 2012; Viel et al., 2018; Cárdenas, 2020)

Note: range means the maximum and minimum value reported in the considered studies.

The results reported in Table 5 show that the highest values of cellulose content are reached by cotton, flax, hemp, ramie and sisal (the average value is 44.16 %). Coconut, coffee chaff, corn, cotton and sugarcane reach greater percentages of hemicellulose (average value=21.83 %); hence, they might demonstrate higher moisture buffering capacity (Cascione et al., 2019). Coconut fibres, hazelnut shells and tea residues show the highest values of lignin (the average value is 20.09%). Therefore, good bonding capacities could be expected for these materials and also better mechanical strength and better resistance to water and microorganisms attack.

4.5 Properties

The properties of bio-wastes vary depending on their chemical composition, plant species, their production and location, climatic characteristics and harvesting (Dittenber and GangaRao, 2012). By knowing those properties and the effect of specific treatments, it is possible to produce building materials with different performances. Using natural wastes and fibres as building materials have simultaneously several advantages and disadvantages. Past studies demonstrate that they frequently improve thermal insulation and acoustic absorption thanks to their high porosity. Furthermore, they can improve indoor hygrothermal conditions favouring indoor comfort. Since bio-wastes usually have good moisture buffering capacity, they can control relative humidity (Mohanty et al., 2005; Dittenber and GangaRao, 2012; Berardi and Iannace, 2015; Sanjay et al., 2018; Nguyen et al., 2018a; Nguyen et al., 2018b; Liuzzi et al., 2020). In addition, many of them have good mechanical properties, they can improve stiffness and strength and they have a high resistance to fracture (Mohanty et al., 2005; Berardi and Iannace, 2015; Sanjay et al., 2018). Natural wastes and natural fibres are recyclable and biodegradable and they guarantee better outcomes for the environment and human health in comparison to synthetic ones. Using bio-wastes is a passive technique that ensures healthier architecture and favours a lower energy impact (Ali, 2016; Ali et al., 2020b). As Nguyen et al. (2017) reported, natural wastes can reduce energy waste for heating and cooling and improve indoor air quality by influencing moisture buffering within a building. Rojas et al. (2019) evaluated the thermal performance of insulation materials made up of natural fibres (wheat straw and corn husk). Researchers demonstrated the feasibility of using these natural fibres. Liuzzi et al. (2018) considered a clay-sand plaster with natural fibres showing that by increasing fibres content, both thermal properties and moisture absorption/desorption improved. Better insulation and control of indoor air ensure lower energy consumption to control the indoor conditions. On the other hand, they have a low resistance to water, microorganism attack and fire. Due to their high porosity, natural wastes can have low dimensional stability and low durability. Even if some appropriate treatments can limit these drawbacks, it is important to consider them for the production of building materials. Table 6 shows a list of some of these advantages and disadvantages.

Table 6 - Advantages and disadvantages of using bio-wastes and natural fibres for the production of eco-efficient construction materials (based on Mohanty et al., 2005; John and Thomas, 2008; Dittenber and GangaRao, 2012; Faruk et al., 2012; Berardi and Iannace, 2015; Nguyen et al., 2017; Liuzzi et al., 2018;).

Advantages	**Disadvantages**
Renewability, recyclability and biodegradability	Hydrophilic nature
Sustainable life cycle, low environmental impact	Degradation at high temperature (problems for pressing at high temperature)
Economical production, low cost	High moisture and water absorption
Non-abrasive	Swelling, dimensional variation
Healthy indoor conditions	Low durability
Insulation properties	Biological susceptibility to moulds
Passive indoor environmental control	Biological susceptibility to insects
Low density	Low resistance to fire

Knowing the properties of natural wastes and fibres allows making considerations on their performance as building materials. The article considers the most studied properties for thermal insulation composites, according to the bibliographic research: density, thermal conductivity, moisture content, and tensile strength. Information related to water absorption and porosity was also investigated, but these values are not reported due to the identified gap in the literature.

Tables 7 and 8 show the results of the analysed studies (published between 2000-2020), making a distinction between raw materials and natural fibres considered alone, and the composite boards. The values change due to the characterization of the fibres, treatment, measurement process and conditions. Table 7 reports values of thermal conductivity, demonstrating the lack of information. Most of the considered studies did not evaluate the thermal conductivity of the raw materials but only of the resulting composites. This is an important outcome justifying further studies related to raw materials. Table 7 gives also information about physical characterization describing the length and diameter of natural fibres. These are important to make preliminary consideration of materials performance. Fibre length influences flexural strength, as indicated by Sanjay et al.

(2018), as well as their content in the composites, which also affects thermal and mechanical properties. For example, Antunes et al. (2019) evaluated board samples made up of rice husk, earth, gypsum and air lime. They demonstrated that higher percentages of fibres improved the insulation properties, whereas mechanical properties (compressive and flexural strength) decreased by changing the rice husk percentage from 15% to 30%. Liuzzi et al. (2016) studied the thermal properties of blends made up of different percentages of clay, sand, straw and cement that can be used for boards or brick production. The results demonstrated that increasing the amount of straw guarantees better thermal performances.

Table 7- Properties of natural raw materials considering studies published between 2000-2020. Where details are not provided in the table, they were not reported in the relevant study.

Materials	Diameter of fibres [µm]	Length [mm]	Moisture content [%]	Density [kg/m³]	Thermal conductivity [W/(m.K)]	Tensile strength [MPa]	References
Banana tree fibres	120	-	-	1350	-	550	(Idicula et al., 2006)
	12-30	300-900	8.7-12	1350	-	500	(Dittenber and GangaRao, 2012)
	80-250	-	-	1350	-	529-759	(Sanjay et al., 2018)
Coffee chaff	-	-	-	70	-	-	(Ricciardi et al., 2017)
Coffee grounds	-	-	-	262-390 [b]	-	-	(Massaro Sousa and Ferreira, 2019)
	-	-	-	-	0.2	-	(Lachheb et al., 2019)
Coffee (dry berry)	-	-	12	422-440 [b]	-	-	(Echeverria and Nuti, 2017)
Coffee (fresh berry)	-	-	65	616-645 [b]; 616 [b] (wet processing)	-	-	(Echeverria and Nuti, 2017)
Coffee (green coffee)	-	-	12	650-750 [b]; 250 [b] (wet processing)	-	-	(Echeverria and Nuti, 2017)
Coir/Coconut	-	-	-	1200	-	175	(Faruk et al., 2012)
	20-150	20-150	-	1150-1460	-	95-230	(Dittenber and GangaRao, 2012)
	100-460	-	-	1150	-	108-252	(Sanjay et al., 2018)
	270-2380	35-50	0.8-3.2	1177 [a]	-	73-505	(Laborel-Préneron et al., 2016)
	-	-	-	1250	-	220	(Jawaid and Abdul Khalil, 2011)
	-	-	-	1200	-	175	(Eichhorn et al., 2001)

Cotton	10-45	10-60	7.85-8.5	1500-1600	-	287-800	(Dittenber and GangaRao, 2012)
	-	-	-	1600	-	287-597	(Sanjay et al., 2018)
	12-35	15-56	-	1510	-	400	(Jawaid and Abdul Khalil, 2011)
	-	-	-	1500-1600	-	287-597	(Eichhorn et al., 2001)
Flax	-	-	-	1500	-	345-1035	(Faruk et al., 2012)
	12-600	5-900	8-12	1400-1500	-	343-2000	(Dittenber and GangaRao, 2012)
	-	-	-	1500	-	345-1500	(Sanjay et al., 2018)
	-	-	7	1530	-	1339	(Summerscales et al., 2010)
	-	33	-	1541	-	-	(Baley, 2002)
	5-38	10-65	-	1400	-	800-1500	(Jawaid and Abdul Khalil, 2011)
		-		1500	-	345-1035	(Eichhorn et al., 2001)
	13	-	-	-	-	-	(Laborel-Préneron et al., 2016)
	-	-	-	-	0.075	-	(Benfratello et al., 2013)
Hazelnut husk	-	-	-	230[*]	-	-	(Çöpür et al., 2007)
Hemp	-	-	-	1480	-	690	(Faruk et al., 2012)
	25-500	5-55	6.2-12	1400-1500	-	270-900	(Dittenber and GangaRao, 2012)
	-	-	-	1480	-	550-900	(Sanjay et al., 2018)
	35	8.5-17	-	1500[a]	-	900-1077	(Laborel-Préneron et al., 2016)
	-		-	-	-	690	(Eichhorn et al., 2001)
	10-51	5-55	-	1480	-	550-900	(Jawaid and Abdul Khalil, 2011)
	-	-	-	-	0.048	-	(Page et al., 2017)
	-	-	-	-	0.04	-	(Romano et al., 2019)

	-	-	-	-	0.051	-	(Laborel-Préneron et al., 2018)
Jute	20-200	1.5-120	12.5-13.7	1300-1490	-	320-800	(Dittenber and GangaRao, 2012)
	-	-	-	1460	-	393-800	(Sanjay et al., 2018)
	1000	20-40	-	1460-1700[a]	-	-	(Laborel-Préneron et al., 2016)
	-	-	-	1300	-	393-773	(Faruk et al., 2012)
	-	-	-	1300	-	393-773	(Eichhorn et al., 2001)
Kenaf	18-37	1.4-11	-	1200	-	295	(Jawaid and Abdul Khalil, 2011)
	-	-	-	1400	-	223-930	(Dittenber and GangaRao, 2012)
	81	-	-	1400	-	250	(Sanjay et al., 2018)
	130	30	-	1040[a]	-	1000	(Laborel-Préneron et al., 2016)
Palm oil	-	-	-	700-1550	-	248	(Faruk et al., 2012)
	150-500	-	-	700-1550	-	80-248	(Dittenber and GangaRao, 2012)
Olive pruning waste	-	-	-	1251[c]	-	-	(Liuzzi et al., 2018)
	-	-	-	-	0.062	-	(Liuzzi et al., 2020)
Pineapple leaves	20-80	-	-	1440	-	413-1627	(Sanjay et al., 2018)
	50	-	-	1526	-	413	(Idicula et al., 2006)
	20-80	3-9	-	-	-	-	(Jawaid and Abdul Khalil, 2011)
Pineapple	-	-	-	800-1600	-	400-627	(Faruk et al., 2012)
	-	-	-	1500	-	170-1627	(Jawaid and Abdul Khalil, 2011)
Ramie	-	-	-	1500	-	560	(Faruk et al., 2012)
	20-80	900-1200	7.5-17	1000-1550	-	400-1000	(Dittenber and GangaRao, 2012)

	-	-	-	1500	-	220-938	(Sanjay et al., 2018)
	-	-	-	-	-	400-938	(Eichhorn et al., 2001)
	18-80	40-250	-	1500	-	500	(Jawaid and Abdul Khalil, 2011)
Sisal	205			1450	-	350	(Idicula et al., 2006)
				1500	-	511-635	(Faruk et al., 2012)
	8-200	900	10-22	1330-1500	-	363-700	(Dittenber and GangaRao, 2012)
	50-300	-	-	1450	-	227-400	(Sanjay et al., 2018)
	150-300	50-72	-	1370 [a]	-	580	(Laborel-Préneron et al., 2016)
	-	-	-	1500	-	511-635	(Eichhorn et al., 2001)
Sugar cane (bagasse)	10-34	10-300	-	1250	-	222-290	(Dittenber and GangaRao, 2012)
	-	-	-	250-350 [b]	0.049-0.055	-	(Liuzzi et al., 2020)
	-	-	-	1250	-	290	(Faruk et al., 2012)
Wheat straw	500-3000	15-50	280-350	868 [a]	0.0414-0.0486	-	(Laborel-Préneron et al., 2016)

Note: [a] Absolute density; [b] Loose bulk density; [c] Real density; *calculate by water displacement method.

Table 8 - Properties of boards with bio-wastes considering studies published between 2000-2020.

Material	**Summary of sample preparation**	**Density [kg/m³]**	**Thermal conductivity [W/(m.K)]**	**References**
Banana bunch	The raw material was pressed by a roll mill, dried at 40°C and cut in chips (<2mm) exposed to a steam pre-treatment, filtered and rinsed. Fibreboards of 3mm thickness and 1000 kg/m³ density were produced by pressing treatment without synthetic binders.	1000	-	(Quintana et al., 2009; Madurwar et al., 2013)
Coconut fibres	Tested specimens were 200mmx400mmx60mm. Thermal conductivity is determined by hotbox apparatus for constant temperatures (T=38°C).	85	0.058	(Ashour et al., 2010)
Coffee chaff	Cylindrical samples (diameter=29 mm and 100mm, thickness from 10 mm to 40 mm) bonded by a cold-water-based polyurethane glue (density=1000 kg/m³). Percentage of 5.5% of the total weight.	346.4	-	(Ricciardi et al., 2017)

	Cylindrical samples (diameter=29 mm and 100mm, thickness from 10 mm to 40 mm) exposed to a hot pressure treatment (maximum pressure of 15,000 kg; T= 140 °C).	960.45	-	(Ricciardi et al., 2017)
	Cylindrical samples (diameter=29 mm and 100mm, thickness from 10 mm to 40 mm) exposed to a cold pressure treatment (maximum pressure of 15,000 kg).	1047.5	-	(Ricciardi et al., 2017)
Corn (Maize) cob	The raw material is granulated and particleboards (250mm x 250 mm x 50 mm) are made with wood glue. Thermal conductivity is determined by using two heat flux meters and by collecting results for seven days. The temperature was continuously measured (T indoor=23°C).	-	0.139	(Pinto et al., 2012)
	Tested boards are low density and are made using hot pressure treatment and urea-formaldehyde resin.	-	0.096	(Panyakaew and Fotios, 2008)
	Samples (250 mm x 250 mm) with different thickness (30 mm, 50 mm, 60 mm and 80 mm) were considered. Wood glue was used as a binder. The method to produce the samples was: mixing the materials, moulding, natural curing and unmoulding. The thermal conductivity value was evaluated using the heat flux method. *Average values (considering different thicknesses). ** Estimated value.	334*	0.101**	(Paiva et al., 2012)
Cotton stalk	The fibres were immersed in water, exposed to a steam treatment (pressure=1.2 bar), and dried at 100°C. Specimens were produced by pressure treatment using a CGM-30 high-frequency press. The binderless fibreboards were then stored at 25°C and 65±5% RH for one week to have a moisture content of 8%. The thermal conductivity of the samples (300mm x 300mm x 25mm) was evaluated at room temperature.	150-450	0.059-0.082	(Zhou et al., 2010; Madurwar et al., 2013; Asdrubali et al., 2015; Nguyen et al., 2017; Liuzzi et al., 2020;)
Date Palm	The thermal conductivity of raw material cut out from the petiole or bunch of the plant wood (samples: 44mm x 44mm and thicknesses between 4.2mm-5mm) is determined by using a periodic method at room temperature.	187-389	0.083	(Agoudjil et al., 2011)
Hazelnut husk	Particles between 0.8 mm-1.5 mm were dried to 3% moisture content at 100–110°C and bonded by urea-formaldehyde, phenol-formaldehyde and melamine-urea formaldehyde. Ammonium chloride was used as a hardener. The boards were pressed at 25 kg/cm² and T=150°C for 6 min and then conditioned at 20±2 1C and 65±5% RH to reach a moisture content of 12%. Particleboards are produced at a pressure of 25 kg/cm² at 150°C for 6 minutes.	600-700	-	(Çöpür et al., 2007)
Hemp	Hemp fibres were chopped, mixed with water, hydraulic lime and hydrated lime and put in a mould. They were removed after 4 days and after one week they were put in a climatic chamber (T=50°C) for 6 days. After reaching a constant mass, thermal conductivity is calculated by a heat flow meter with the plates at 5°C and 25°C.	369-475	0.0899-0.1079	(Benfratello et al., 2013; Nguyen et al., 2018b)
Kenaf	The raw material was cut in chips (thickness of 0.5 mm) and the particles were air-dried to 12% moisture content. A sealed steam injection press allowed the mat pressing (pressure=1.10 MPa at 183°C for 7-10 minutes). Finally, the binderless boards were conditioned at room temperature and reach a moisture content of 5%–7%. Thermal conductivity is evaluated according to the American Society for Testing Materials (ASTM C518-17a).	150-200	0.051-0.058	(Xu et al., 2004; Madurwar et al., 2013)

Pineapple leaves	The board was made of dried shredded pineapple leaves and natural rubber latex as a binder. The leaves were manually cut, soften in NaOH solution for 30 minutes, dried at T=80°C for 12h, mechanically cut and dried again at T=80°C for 12h. Then natural rubber was spread in different ratios to produce specimens of 200mmx200mmx15mm.	178-232	0.035-0.043	(Tangjuank, 2011; Asdrubali et al., 2015)
Rice husk	Boards were made of rice husk (30% by volume of earth), earth, hemihydrate gypsum (20% by volume of earth) and air lime (10% by volume of earth). Earth, gypsum, lime and water were mixed for 90 s. then rice husk was added and mixed mechanically for 1 min. The samples were moulded, dried at T=23 °C 50% RH for 2 weeks, demoulded and tested after two more weeks. Thermal conductivity is evaluated by using an ISOMET 2104 Heat Transfer Analyser equipment at T=23 °C and RH=50%. *Only the composition with 30% rice husk is reported as show the best thermal insulation performances.	650.8	0.102	(Antunes et al., 2019)

Note: No data is presented when it is not provided by the considered reference.

Density and thermal conductivity are extremely important for insulation properties, board production and application on buildings. They are strictly connected, and they widely affect porosity (Chikhi et al., 2013; Palumbo et al., 2016; Nguyen et al., 2017; Nguyen et al., 2018b; Nguyen et al., 2020). The lower the density and thermal conductivity, the better is the thermal insulation performance, as Panyakaew and Fotios (2011) reported. In terms of raw material density, there are many different values because of the different characteristics of the fibres and crops. Board density is lower due to its constituents and the production method. Considering thermal conductivity, it is possible to note that several materials have promising values, both for raw material and when used in boards. Normally for a thermal insulation element, thermal conductivity is lower than 0.065 W/(m.K) (AFNOR, 1983).

Figures 2 and 3 show the comparison between considered particleboards and an insulation expanded corkboard (ICB), already commercially widespread and used. Considering Tártaro et al. (2017) and Fu et al. (2020), ICB has a density of 100-114 kg/m³ and thermal conductivity of 0.042 W/(m.K). The results demonstrate good insulating properties of bio-wastes and the feasibility of using them for boards’ production. Figure 4 shows the correlation between thermal conductivity and density considering Table 8.

Figure 2

Figure 3

Figure 4

Tensile strength is another widely studied property, especially for reinforced composites with natural fibres. Past research reported that cellulose contents and length of the fibres influence their tensile strength (John and Thomas, 2008; Faruk et al., 2012; Nguyen et al., 2018a), a longer fibre length results in lower values. Considering the tensile properties of the raw materials, shown in Table 7, it is difficult to define the relationship between the percentage of cellulose, fibre length and tensile strength. The values are extremely different from each other and the range is too large.

5. Bio-wastes from the Euro-Mediterranean area suitable for building products and associated challenges

As previously described, this article focuses on Euro-Mediterranean countries (Table 4) where thermal retrofitting is needed in many traditional buildings. That retrofitting must be compatible with the existent walls and should be eco-efficient.

5.1 Selected bio-wastes from the Euro-Mediterranean area

Several past studies have considered the four wastes chosen (section 4.3) as possible building materials and evaluated their thermal performances. Liuzzi et al. (2020) investigated olive pruning waste and barley straw to produce an insulating board, and a mixture of clay sand and olive fibres to produce a plaster (Liuzzi et al., 2018). Both studies demonstrated that higher contents of olive fibres improved thermal performances.

Eliche-Quesada et al. (2011) described the feasibility of adding coffee grounds to clay for brick production. They demonstrated that this bio-waste reduced density and increased insulation performances and porosity. Kua et al. (2016) investigated the optimum composition to produce a geopolymeric material using coffee grounds, fly ash and blast furnace slag. Lachheb et al. (2019) demonstrated that adding coffee grounds improved the thermal properties of an industrial gypsum plaster with a density of 1150 kg/m³.

For waste pomace from wine production, Muñoz et al. (2014) and Taurino et al. (2019) tested clay bricks with the addition of this bio-waste. They both obtained building elements with lower bulk density, higher porosity and better insulation properties in comparison to a reference sample. Wine wastes also reduced linear drying shrinkage. Pedras et al. (2020) studied the chemical characterization of red wine grape pomace and said that lignin content is rather high. This information can suggest possible adhesive properties of the bio-waste.

Studies with hazelnut shells (Çöpür et al. 2007) showed the possibility of producing particleboards using urea-formaldehyde, phenol-formaldehyde and melamine-formaldehyde as binders. They demonstrated that this is a feasible solution, and this bio-waste can be used for board production. Nevertheless, these have lower dimensional stability (higher thickness swelling and water absorption) than wood-particleboards. This may be solved using a water repellent.

The sustainability of using these bio-wastes for building products is supported also by information related to their collection. For example, Dam and Harmsen, (2010) reported that spent coffee grounds are not suitable for burning and are therefore disposed of in landfills together with domestic and commercial solid waste. Past studies (Dam and Harmsen, 2010; Echeverria and Nuti, 2017) addressed different practices to reuse them such as animal feed, composting and fermentation. Pedras et al. (2020) reported that agro-wastes are often used for animal feed, citing olive pomace, grape pomace and coffee grounds. Hazelnut shells are normally used for combustion and heating (Lopes et al., 2012; Demirer et al., 2018).

Table 9 collects information related to the chemical composition and properties of these four selected materials. For cellulose, hemicelluloses and lignin contents, past studies reported much information. On the contrary, extractives, waxes and ashes are not reported in Table 9 due to a lack of data in the analysed articles.

Table 9 - Chemical composition and properties of four selected bio-wastes from spent coffee, wine production, hazelnut shells and olive oil production.

Material	**Chemical composition [%]**			**Properties - raw materials**		**References**
	Cellulose	**Hemicelluloses**	**Lignin**	**Density [kg/m^3]**	**Thermal conductivity [W/(m.K)]**	
Coffee grounds	8.60-52.42	6.80-44.50	18.30-24.52	380 ^{b}	0.20	(Muñoz Velasco et al., 2016; Zarrinbakhsh et al., 2016; Buratti et al., 2018; Ribeiro et al., 2018; Lachheb et al., 2019; Massaro Sousa and Ferreira, 2019; Pedras et al., 2019)
Grapes (waste pomace)	15.00-50.16	6.62-11.30	30.30	-	-	(Barbieri et al., 2013; Muñoz et al., 2014; Pedras et al., 2020)
Vine shoots	41.14	26.00	20.27	105 ^{b}	-	(Cárdenas, 2020; Wong et al., 2020)
Hazelnut shells	22.90-34.60	11.30-23.50	30.20-41.40	230*	0.10	(Çuhadaroğlu, 2005; Çöpür et al., 2007; Guler et al., 2008; Salasinska and Lopes et al., 2012; Ryszkowska, 2012; Licursi et al., 2017)
Olive husks	25.00	24.60	50.40	-	-	(García et al., 2016)
Olive whole stones	31.90	21.90	26.50	-	-	(Fernández-Bolaños et al., 1999)
Olive seed husks	36.40	26.80	26.00	-	-	(Fernández-Bolaños et al., 1999)

Olive pruning waste	-	-	-	1251 ^{a}	0.062	(Liuzzi et al., 2018; Liuzzi et al., 2020)

Note: ^{a} Real density; ^{b} Loose bulk density; *calculate by water displacement method.

The selected materials have percentages of cellulose lower than the average value of Table 5 (44.16 %), contents of hemicellulose similar to the average value (21.83 %) and higher content of lignin (average value= 20.09%). Hazelnut shells, coffee grounds and grape waste pomace have the highest values of cellulose and lignin, hence they could show adhesive properties. Coffee grounds and hazelnut shells have the highest values of hemicelluloses. Considering the information provided in Section 4.4, they could not guarantee good resistance to water, but they may provide good moisture buffering capacity.

Considering the properties previously analysed (density, thermal conductivity, moisture content and tensile strength), there is a gap in the literature. It will be interesting to define the properties of each bio-waste as raw material and then deepen the information related to boards, made from these bio-wastes and eventually a binding agent. Since the selected materials seem to have promising thermal behaviour, based on previous past studies, future research can deepen this knowledge to propose innovative sustainable building products. These considerations should be verified by experimental tests that evaluate the properties of the selected bio-wastes relating them with their chemical composition.

5.2 General problems of using bio-wastes for building materials

Although the use of bio-wastes particles and fibres for building products has several advantages, it also involves some drawbacks, as Table 6 previously described. It is important, taking into consideration also this aspect, to ensure proper use of these resources. Knowing the disadvantages of bio-wastes and fibres in building products allows the prevention of problems deriving from their use. Considering past studies, several examples of problems of using bio-wastes are reported, as the hydrophilic nature, high moisture and water absorption, low dimensional stability, durability and resistance to fire, and increased susceptibility to moulds and insects (Mohanty et al., 2005; John and Thomas, 2008; Dittenber and GangaRao, 2012; Faruk et al., 2012; Berardi and Iannace, 2015; Nguyen et al., 2017; Liuzzi et al., 2018). Some of these are detailed in this section.

One of the most investigated disadvantages of bio-wastes is their hydrophilic nature (Dittenber and GangaRao, 2012; Jawaid and Abdul Khalil, 2011; Nguyen et al., 2020). This property can determine also positive behaviours, depending on the type of construction element. It results in high moisture adsorption capacity whilst also allowing a passive control of the indoor condition. At the same time, it entails low dimensional stability, high swelling of the fibres if in contact with water and lower mechanical properties (Nguong et al., 2013; Faruk et al., 2012; John and Thomas, 2008). As reported in Table 6, these are recognized drawbacks of using natural fibre products and bio-aggregates for building practices. To mitigate these problems, it could be necessary using additives to control hygroscopic behaviour and mechanical properties.

Another disadvantage of lignocellulosic materials is their high flammability. As Aladejana et al. (2020) said, fire resistance is one of the most important properties for building materials. Nowadays some bio-materials made of natural wastes and fibres do not guarantee the required properties without using solutions that correct this shortcoming (Liu et al., 2017). The high flammability of lignocellulosic materials limits their application without specific treatments and fire retardants (Belayachi et al., 2017; Prakash Chaudhari and Bhole, 2020). This can lead to higher costs and higher production times, and sometimes to lower sustainability. In addition, both flame exposure and flame retardants can adversely affect the mechanical properties of natural fibres, as Kim et al. (2018) reported.

Several studies (John and Thomas, 2008; Berardi and Iannace, 2015; Liuzzi et al., 2017; Antunes et al.,2019; Owodunni et al., 2020b) pointed out another significant drawback: being organic elements, they are more susceptible to fungi, mould and insects attack. As Palumbo et al. (2017) reported, to evaluate the feasibility of using agricultural wastes for building products, fire resistance and fungal susceptibility are the two most important issues to consider. Depending on the material and the construction element, the possible biological attacks will be different. It varies according to environmental conditions (temperature and relative humidity) and materials properties such as nutrient content, chemical composition and hygroscopicity (Palumbo et al., 2017; Viel et al., 2019b). Specific treatments can mitigate this problem, but research into suitable treatments for bio-based materials and natural fibres is limited and warrants further research (Liuzzi et al., 2017). More information related to biological susceptibility is reported later.

Finally, since the article studies agro-industrial waste, it is important to consider the harmful effects that agricultural practices could have on the environment. Some crops, intensive cultivations and agricultural trade could degrade natural resources. They could cause deforestation, soil erosion, overuse of water, pollution and negative effects on the biodiversity of animal and vegetal species (Hosonuma et al., 2012; Dudley and Alexander, 2017; Balogh and Jámbor, 2020). For example, Foster et al. (2011) and Savilaakso et al. (2014) pointed out the harmful effects of the cultivation of palm oil, highlighting the impact on biodiversity and high carbon emission. Beyer et al. (2020) reported these effects for the cultivation of soybean, rapeseed, sunflower and groundnut oil, albeit in lower amounts. Several studies reported that rice cultivations are responsible for the emission of greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Cai et al., 2003; Anand et al., 2005; Bhattacharyya et al., 2012). Furthermore, many crops require a high amount of water. Water demand is increasing and causes several environmental problems (Boretti and Rosa, 2019; Guerrero-Baena and Gómez-Limón, 2019). Hence, it is important to take into consideration that the use of agro-industrial bio-wastes to ensure a more sustainable architecture must not lead to higher environmental impacts caused by agricultural practices.

5.3 Biological susceptibility

To carry out future research related to bio-insulation boards, increased biodeterioration risk is one of the most important drawbacks to consider. Several past studies evaluated this problem considering boards made up of bio-wastes and fibres. For example, Antunes et al. (2019) considered the biological susceptibility of a rice husk, earth, gypsum and air lime board concluding that, as expected, it increases with a higher content of rice husk. Monteiro et al. (2020) studied the biological susceptibility of particleboards made up of maritime pine, cardoon (*Cynara cardunculus* L.) and a starch-based bio-binder. They considered subterranean termites and wood decay fungi (*Gloeophyllum trabeum* (Pers.) Murrill) demonstrating a high susceptibility of cardoon and starch. Farag et al. (2020) analysed particleboards made up of olive stone and a polyester liquid resin as a binder, concluding that this binding material ensures good protection from fungal and bacteria attack. Palumbo et al. (2017) evaluated mould growth of an insulation board composed of corn pith, sodium alginate and some additives that mitigate fire and biological susceptibility (boric acid, aluminium hydroxide, ammonium polyphosphate, montan wax, acetic acid and lactic acid).

Curling (2017) highlighted the importance of temperature and moisture content for biological growth and described different methods to evaluate the susceptibility of the materials to biodeterioration agents such as moulds, decay fungi or insects, making a distinction between laboratory, field and service life tests and monitoring. Stefanowski et al. (2017) evaluated mould growth of specimens made up of corn pith and additives by a rapid screening method. The researchers highlighted the influence of hygric properties in biological attack and they gave a list of mould species that are normally found in indoor environments. Parracha et al. (2021) monitored the biological susceptibility to moulds of External Thermal Insulation Composite System (ETICS) adapting a method from two American standards (ASTM D5590-17b and ASTM C1338-19). A mixed spore suspension of two common moulds was applied on the surface of the specimens and the biological growth analysed during a four weeks exposure period. Visual grading was used to evaluate the biological growth that was very restricted due to the presence of biocides or the high pH of the surfaces.

To prevent biodeterioration Liu et al. (2017) suggested the use of a multilayer structure including the application of biocides and keeping the materials in dry condition. An alternative is the use of some natural materials that can prevent this problem such as air lime. Santos et al. (2017) used air lime to prevent fungal colonization in an earth-based mortar. Bumanis et al. (2020) reported a past study that demonstrated an improvement in the biological resistance of gypsum-based mortar by adding lime additives. Citric acid has widely been investigated as a fungal growth deterrent (Essoua Essoua et al. 2016). Furthermore, Lee et al. (2020) reported that it improves the biological resistance of wood and particleboards if used as a bio-binder.

6. Conclusions

It has been widely demonstrated that using natural fibres and other bio-wastes for building products is a feasible and efficient possibility. To guarantee more sustainable solutions, bio-wastes could be considered to produce building products, such as particleboards, insulation boards, masonry units and mortars. Since they are constantly and widely produced, namely but not exclusively for feeding mankind and animals, they are available in large quantities. Sometimes they cause negative effects by increasing environmental problems and their disposal can be a problem. Employing them in buildings both improves recycling practices and may guarantee eco-effective solutions.

This article collects information considering past studies related to the use of natural fibres and other bio-materials for building products, focusing on bio-wastes. First, it investigates bio-materials already studied for construction practices. Then it gives a classification of bio-wastes and details the ones derived from agriculture practices and agro-industrial processes, aiming at selecting some of them to carry out future studies. It collects information about worldwide production, chemical composition, physical and mechanical properties. Knowing world production and the ranking of the major producers of crops allows taking into consideration the origins of bio-wastes, so helping to minimise environmental impact. Since transport and production of building materials are responsible for high energy consumption, this information for potential local supplies offers solutions to ecological problems. Bio-wastes derived from either olive oil and wine production or hazelnut and coffee consumption were chosen for further work in order to achieve innovative sustainable solutions.

The analysis of chemical composition gave a preview of the possibilities derived from the use of a specific natural material, but further studies are needed. Since the agro-industrial wastes are lignocellulosic materials, they have similar components: cellulose, hemicelluloses and lignin with other natural substances, such as extractives, pectin, waxy substances and ash. Each one affects the performances differently, hence knowing their percentages is useful information to preview the possible properties of the composite materials produced with them. Information related to these aspects was collected for all the agro-industrial wastes considered and then was further investigated for the four selected bio-wastes.

For physical and mechanical properties, this study made a distinction between bio-wastes and boards produced using them. This gave useful information for future research related to board production. Several studies demonstrated that using natural wastes in building products, such as plasters, brick and particleboards, often determines lower values of density and thermal conductivity and higher porosity.

For properties of raw materials, the collected information shows there is a lack of information concerning thermal conductivity and water absorption. Future research should further characterize the agro-industrial bio-wastes considered in this article, evaluating them as raw materials which can be extremely useful to develop a decision tool for the choice of materials for composites. Among the considered past studies related to board production, boards made of dried shredded pineapple leaves have the lowest conductivity (0.035-0.043 W/(m.K)), while the ones with coconut fibres and palm oil boards reach the lowest values of density (85 kg/m^3). Several studies lack important information concerning the specimens' preparation and curing to allow comparison of results, such as the initial drying of the materials, the pre-processing and some information on the production method of the specimens (aggregate-glue mixing method, information related to moulding and demoulding), conditioning of specimens and measurement method.

This future research, based on the data collection presented in this work will contribute to the use of bio-wastes in building products, reduce the gaps of knowledge found in literature and propose innovative, efficient, and more sustainable materials.

CRediT authorship contribution statement

Eleonora Cintura: Conceptualization, Investigation, Formal analysis, Data Curation, Writing - Original Draft, Visualization; **Lina Nunes**: Conceptualization, Writing - Review & Editing, Supervision, Project administration; **Bruno Esteves**: Writing - Review & Editing; **Paulina Faria**: Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Figures

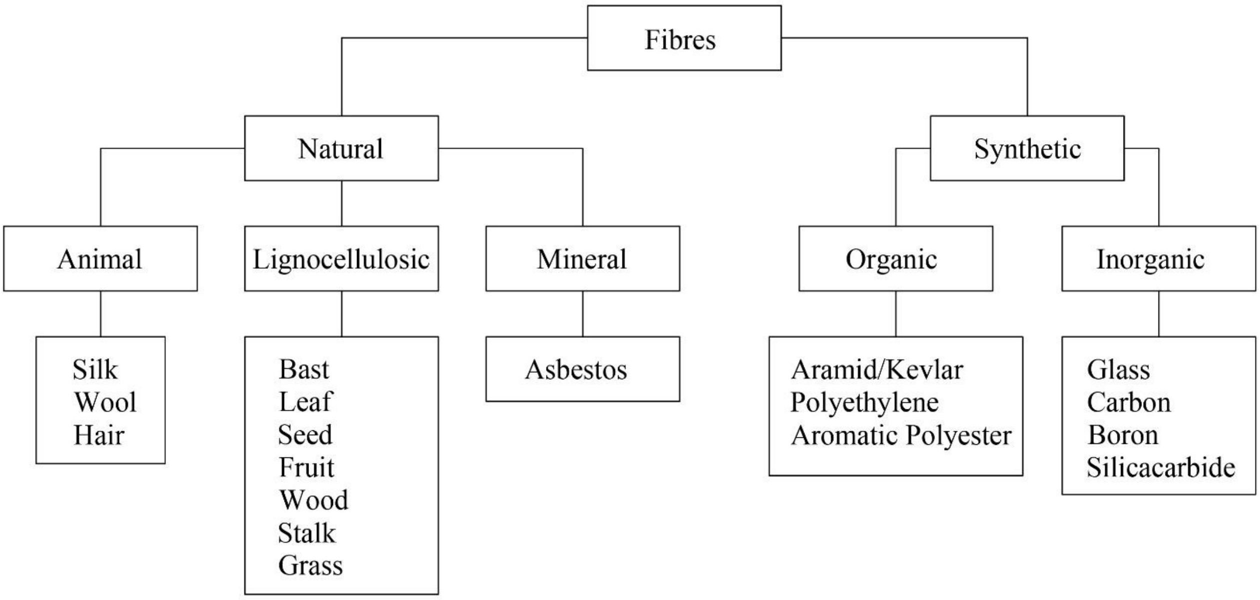

Figure 4 - Classification of natural and synthetic fibres (adapted from Jawaid and Abdul Khalil, 2011).

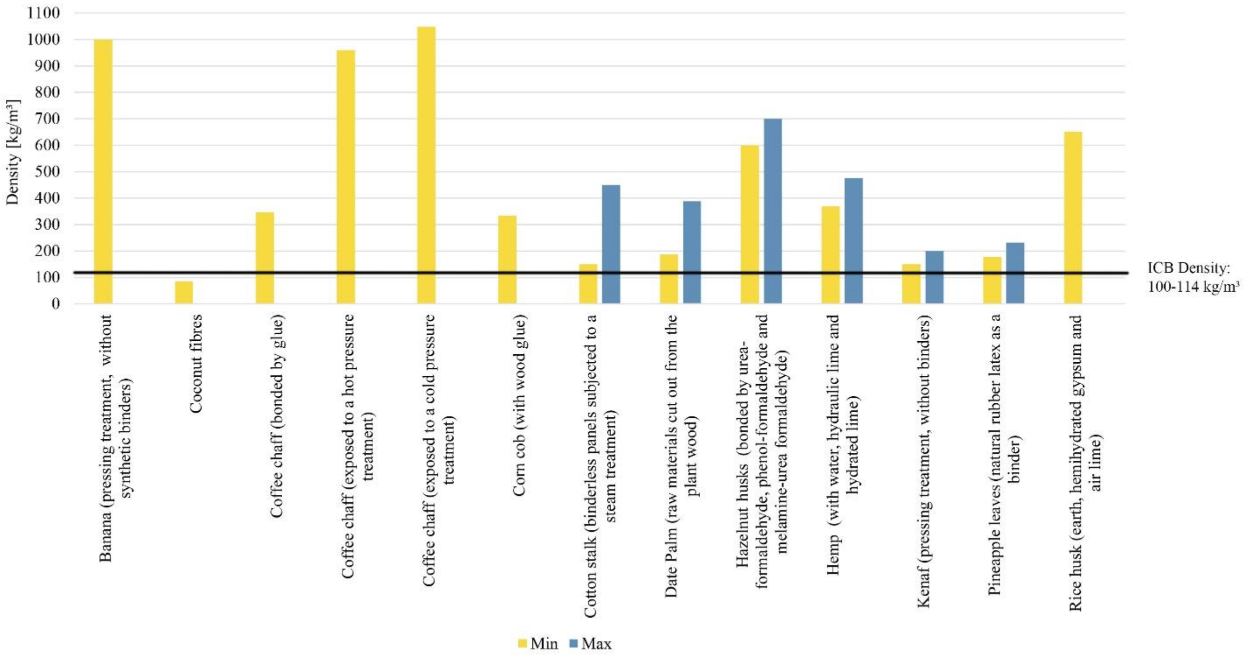

Figure 5 - Density of particleboards with different bio-wastes (based on Table 8) compared with density of insulation expanded corkboard (ICB).

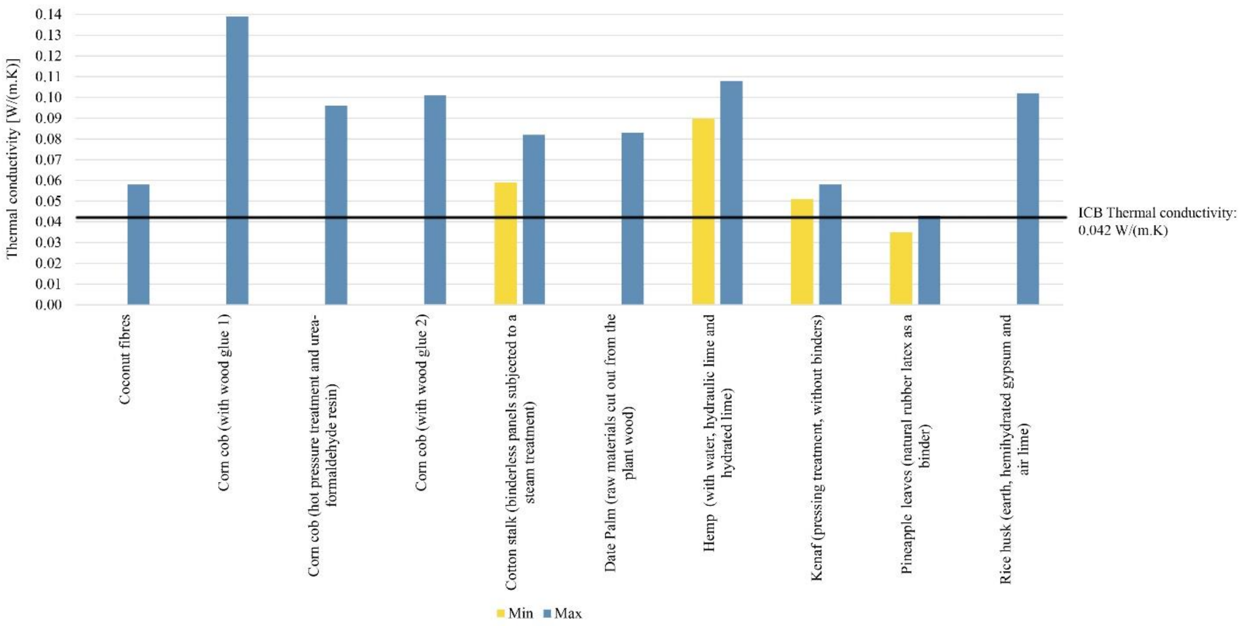

Figure 6 - Thermal conductivity of particleboards with different bio-wastes (based on Table 8) compared with thermal conductivity of insulation expanded corkboard (ICB).

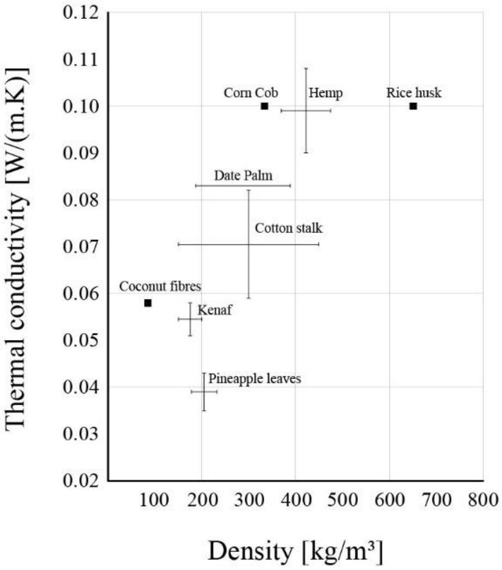

Figure 4 - Correlation between thermal conductivity and density of boards with bio-wastes (based on Table 8).

Supplementary material

Table SM1 reports the detailed results related to the chemical composition of agro-industrial wastes used for building materials considered in table 3 in the article.

Table SM1 - Chemical composition of several bio-wastes considering research works published in the last twenty years (2000-2020).

Material	Chemical composition [%]					References
	Cellulose	**Hemicelluloses**	**Lignin**	**Waxes**	**Ash**	
Banana	60.00-65.00	19.00	5.00-10.00	-	-	(Jawaid and Abdul Khalil, 2011)
	63.00-67.60	10.00-19.00	5.00	-	-	(Dittenber and GangaRao, 2012)
	63.00-64.00	19.00	5.00	-	-	(Idicula et al., 2006)
	64.00	10.00	5.00	-	-	(Nguong et al., 2013)
Range	**60.00-65.00**	**10.00-19.00**	**5.00-10.00**	-	**-**	
Coconut fibres/coir	64.00	-	-	-	0.74	(Phan et al., 2006)
	51.12	67.63	36.73	-	-	(Panyakaew and Fotios, 2011)
	31.60	25.50	35.10	-	-	(Nascimento et al., 2016)
	52.20	28.40	19.40	-	-	(García et al., 2016)

	32.00-43.80	0.15-20.00	40.00-45.00	-	-	(Dittenber and GangaRao, 2012)
	32.00-43.00	0.15-0.25	40.00-45.00			(Faruk et al., 2012)
	-	-	45.84	-	-	(Khedari et al., 2004)
	32.00-43.00	0.15-0.25	40.00-45.00	-	-	(Jawaid and Abdul Khalil, 2011)
	21.00-43.00	0.25-22.00	27.00-47.00	-	-	(Zhou et al., 2010)
Range	**21.00-64.00**	**0.15-67.63**	**19.40-47.00**	**-**	**0.74**	
Coffee chaff	22.83	19.30	28.59	-	5.94	(Buratti et al., 2018)
	13.00-24.00	11.00-12.00	21.00-32.00	-	-	(Quosai et al., 2018)
	23.60	12.10	17.80	-	6.90	(Zarrinbakhsh et al., 2016)
Range	**13.00-24.00**	**11.00-19.30**	**17.80-32.00**	**-**	**5.94-6.90**	
Coffee grounds	8.80	44.50	13.10	-	-	(Pedras et al., 2019)
	10.00	40.00	20.00	-	-	(Ribeiro et al., 2018)
	8.60	36.70	-	-	1.60	(Lachheb et al., 2019)
	49.65	6.80	-	-	0.98	(Muñoz Velasco et al., 2016)
	52.42	7.20	-	-	1.33	(Muñoz Velasco et al., 2016)
	12.31	33.44	24.52	-	2.52	(Buratti et al., 2018)
	23.00	19.40	18.30	-	2.20	(Zarrinbakhsh et al., 2016)
Range	**8.60-52.42**	**6.80-44.50**	**18.30-24.52**	**-**	**0.98-2.52**	
Corn (Maize) cobs	33.70-41.20	31.9-36.6	6.10-15.90	-	-	(Cárdenas, 2020)
	36.78	38.81	3.30	-	0.46	(Viel et al., 2018)
	38.80	44.40	11.90	-	2.88	(Viel et al., 2018)
	36.78	38.81	30.30	-	0.46	(Viel et al., 2019) (after alkali treatment)
	48.10	37.20	14.70	-	-	(García et al., 2016)
Range	**33.70-48.10**	**31.90-44.40**	**3.30-30.30**	**-**	**0.46-2.88**	
Corn cob residues	27.10	13.87	0.64	-	0.43	(Viel et al., 2019) (after alkali treatment)
Corn (Maize) stalks	35.00-39.60	16.80-35.00	7.00-18.40	-	-	(Cárdenas, 2020)
Corn stover	47.40	30.30	22.30	-	-	(García et al., 2016)
Cotton	71.60	42.50	20.50	-	5.54	(Pirayesh and Khazaeian, 2012)
	58.48	14.38	21.45	-	-	(Cárdenas, 2020)
	82.70-90.00	5.70	<2	0.60	-	(Dittenber and GangaRao, 2012)
	82.70	5.70	-	-	-	(Jawaid and Abdul Khalil, 2011)
	88.00	5.70	-	0.60	-	(Nguong et al., 2013)
	87.50	17.10	-	-	-	(García et al., 2016)
Range	**58.48-90.00**	**5.70-42.50**	**2.00-21.45**	**0.60**	**5.54**	

Cotton stalk	66.20	18.40	15.40	-	-	(García et al., 2016)
	32.00-46.00	20.00-28.00	26.00	-	8.16	(Nguyen et al., 2017)
Range	**32.00-66.20**	**18.40-28.00**	**15.40-26.00**	**-**	**8.16**	
Flax	71.00	18.60-20.60	2.20	1.50	-	(Faruk et al., 2012)
	34.90	23.60	22.30	-	-	(Cárdenas, 2020)
	28.51	15.80	18.14	-	4.20	(Viel et al., 2019)
	62.00-72.00	18.60-20.60	2.00-5.00	1.50-1.70	-	(Dittenber and GangaRao, 2012)
	61.00	27.00	8.00	-	-	(Laborel-Préneron et al., 2016)
	81.00	14.00	3.00	-	-	(Laborel-Préneron et al., 2016)
	60.00	16.00	3.00	-	-	(Laborel-Préneron et al., 2016)
	64.10	16.70	2.00	-	-	(Jawaid and Abdul Khalil, 2011)
	71.00	19.60	2.20	1.70	-	(Nguong et al., 2013)
	75.90	20.70	3.40	-	-	(García et al., 2016)
	62.00-72.00	18.60-20.60	2.00-5.00	1.50-1.70	-	(Papadopoulou et al., 2015)
Flax shiv	44.63	24.41	20.98	-	1.48	(Viel et al., 2018)
	38.06	25.03	31.20	-	1.71	(Viel et al., 2018)
	53.00	13.00	24.00	-	>2	(Viel et al., 2018)
	39.90	26.80	24.20	-	-	(García et al., 2016)
Range	**28.51-81.00**	**13.00-27.00**	**2.00-31.20**	**1.50-1.70**	**1.48-4.20**	
Flax fine	28.51	15.80	18.14	-	4.20	(Viel et al., 2018)
Flax fine residues	16.21	5.83	7.74	-	2.92	(Viel et al., 2019)
Grapes (waste pomace)	15.00	11.30	30.30	-	7.00	(Pedras et al., 2020)
	-	-	-	-	3.70	(Muñoz et al., 2014)
	50.16	6.62	-	-	-	(Barbieri et al., 2013)
Range	15.00-50.16	6.62-11.30	30.30	-	3.70-7.00	
Hazelnuts	55.10	34.60	41.40	-	8.23	(Pirayesh and Khazaeian, 2012)
	55.10	34.50	35.10	-	8.22	(Çöpür et al., 2007)
Range	**55.10**	**34.50-34.60**	**35.10-41.40**	**-**	**8.22-8.23**	
Hazelnut shells	34.00	20.00	35.00-41.00	-	-	(Salasinska and Ryszkowska, 2012)
	34.50	-	35.10	-	8.22	(Çöpür et al., 2007)
	22.90	23.50	-	-	1.40	(Licursi et al., 2017)
	34.60	-	41.40	-	-	(Guler et al., 2008)
	28.90	11.30	30.20	-	4.00	(Lopes et al., 2012)
Range	**22.90-34.60**	**11.30-23.50**	**30.20-41.40**	**-**	**1.40-8.22**	
Hemp	74.40	17.90	3.70	-	-	(Jawaid and Abdul Khalil, 2011)
	68.00-74.40	15.00-22.40	3.70-10.00	0.80	-	(Dittenber and GangaRao, 2012)
	67.00-78.30	5.50-16.10	2.90-3.30	-	-	(Summerscales et al., 2010)
	64.00	16.00	4.00	-	-	(Laborel-Préneron et al., 2016)

	67.00	5.50	2.90	-	-	(Shalwan and Yousif, 2013)
	72.00	20.10	4.70	0.80	-	(Nguong et al., 2013)
	68.00-74.40	15.00-22.40	3.70-10.00	0.80	-	(Papadopoulou et al., 2015)
Hemp shiv	49.97	21.42	9.52	-	0.67	(Viel et al., 2018)
	51.60	21.50	12.90	-	6.60	(Viel et al., 2018)
	47.50	6.40	8.00	-	8.80	(Viel et al., 2018)
	44.00	18.00	28.00	-	2.00	(Viel et al., 2018)
Hemp fines	42.66	18.87	11.52	-	1.62	(Viel et al., 2018)
Range	**44.00-78.30**	**5.50-22.40**	**2.90-28.00**	**0.80**	**0.67-8.80**	
Jute	61.00-71.00	14.00-20.00	12.00-13.00	0.50	-	(Faruk et al., 2012)
	64.40	12.00	11.80	-	-	(Jawaid and Abdul Khalil, 2011)
	59.00-71.50	13.60-20.40	11.80-13.00	0.50	-	(Dittenber and GangaRao, 2012)
	72.00	13.00	13.00	-	-	(Laborel-Préneron et al., 2016)
	33.40	22.70	28.00	-	-	(Madurwar et al., 2013)
	58.00-63.00	20.00-22.00	-	-	0.62	(Phan et al., 2006)
	66.00	17.00	12.50	0.50	-	(Nguong et al., 2013)
Range	**33.40-72.00**	**12.00-22.70**	**11.80-28.00**	**0.50**	**0.62**	
Kenaf	72.00	20.30	9.00	-	-	(Faruk et al., 2012)
	31.00-72.00	20.30-21.50	8.00-19.00	-	-	(Dittenber and GangaRao, 2012)
	70.00	3.00	19.00	-	-	(Laborel-Préneron et al., 2016)
	53.40	33.90	21.20	-	4.00	(Jawaid and Abdul Khalil, 2011)
	51.00	21.50	10.50	-	-	(Nguong et al., 2013)
	31.00-72.00	20.30-21.50	8.00-19.00	-	-	(Papadopoulou et al., 2015)
Range	**31.00-72.00**	**3.00-33.90**	**8.00-21.20**	**-**	**4.00**	
Palm oil	60.00-65.00	-	11.00-29.00	-	-	(Dittenber and GangaRao, 2012)
	49.00	21.00	23.00	-	-	(Laborel-Préneron et al., 2016)
	65.00	-	19.00	-	2.00	(Jawaid and Abdul Khalil, 2011)
Range	**49.00-65.00**	**21.00**	**11.00-29.00**	**-**	**2.00**	
Palm oil frond	56.03	27.51	20.48	-	2.40	(Jawaid and Abdul Khalil, 2011)
Olive husks	25.00	24.60	50.40	-	-	(García et al., 2016)
	-	-	-	-	14.21	(Christoforou et al., 2017)
Olive whole stones	31.90	21.90	26.50	-	-	(Fernández-Bolaños et al., 1999)
Olive seed husks	36.40	26.80	26.00	-	-	(Fernández-Bolaños et al., 1999)
Olive pomace	-	-	-	-	3.20-8.63	Christoforou et al., 2017)
Pineapples	81.00	-	12.70	-	-	(Idicula et al., 2006)

Ramie	68.60-76.20	13.00-16.00	0.60-0.70	0.30	-	(Faruk et al., 2012)
	68.60-85.00	13.00-16.70	0.50-0.70	0.30	-	(Dittenber and GangaRao, 2012)
	68.60	13.10	0.60	-	-	(Jawaid and Abdul Khalil, 2011)
Range	**68.60-85.00**	**13.00-16.70**	**0.50-0.70**	**0.30**	**-**	
Rice husk	35.00-45.00	19.00-25.00	20.00	14.00-17.00	-	(Faruk et al., 2012)
	30.00	20.00	33.00	-	14.00	(Brás et al., 2019)
Range	**30.00-45.00**	**19.00-25.00**	**20.00-33.00**	**14.00-17.00**	**14.00**	
Rice straw	41.00-57.00	33.00	8.00-19.00	8.00-38.00	-	(Faruk et al., 2012)
	36.20-47.00	19.00-24.50	9.90-24.00	-	-	(Cárdenas, 2020)
	52.30	32.80	14.90	-	-	(García et al., 2016)
Range	**36.20-57.00**	**19.00-33.00**	**8.00-24.00**	**8.00-38.00**	**-**	
Sisal	65.00	12.00	9.90	2.00	-	(Faruk et al., 2012)
	65.80	12.00	9.90	-	-	(Jawaid and Abdul Khalil, 2011)
	65.00	12.00	9.90	-		(Idicula et al., 2006)
	60.00-78.00	10.00-14.20	8.00-14.00	2.00	-	(Dittenber and GangaRao, 2012)
	65.80	12.00	9.90	-	-	(Laborel-Préneron et al., 2016)
	73.00	13.00	11.00	-	-	(Laborel-Préneron et al., 2016)
	38.20	26.00	26.00	-	-	(Madurwar et al., 2013)
	73.00	12.00	12.00	2.00	-	(Nguong et al., 2013)
Range	**38.20-78.00**	**10.00-26.00**	**8.00-26.00**	**2.00**	**-**	
Sugar cane (bagasse)	55.20	16.80	25.30	-	-	(Faruk et al., 2012)
	32.00-55.20	16.80	19.00-25.30	-	-	(Dittenber and GangaRao, 2012)
	40.00-41.30	27.00-37.50	10.00-20.00	-	-	(Cárdenas, 2020)
	47.40	29.10	23.50	-	-	(García et al., 2016)
Range	**32.00-55.20**	**16.80-37.50**	**10.00-25.30**	**-**	**-**	
Sunflower seed	24.10	28.60	29.40	-	-	(Cárdenas, 2020)
Sunflower stalks	42.10	29.66	13.44	-	-	(Cárdenas, 2020)
Sunflower whole plant	23.93	7.83	9.13	-	-	(Evon et al., 2012)
Sunflower shells	66.20	18.40	15.40	-	-	(García et al., 2016)
Tea residue	33.30	23.20	43.50	-	-	(García et al., 2016)
Vine shoots	41.14	26.00	20.27	-	-	(Cárdenas, 2020)
Wheat straw	38.00-45.00	15.00-31.00	12.00-20.00	-	-	(Faruk et al., 2012)
	32.90-50.00	24.00-35.50	8.90-17.30	-	-	(Cárdenas, 2020)
	43.04	29.66	5.24	-	0.82	(Viel et al., 2018)
	38.60	32.60	14.10	-	5.90	(Viel et al., 2018)
	45.00	28.00	18.00	-		(Karade, 2010)
Range	**32.90-50.00**	**15.00-35.50**	**5.24-20.00**	**-**	**0.82-5.90**	