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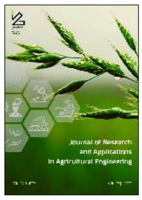

Herbal-plant Residues as Potential Raw Materials Source for Particleboard Production: A Review

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wood-based panels

The suitability of plant waste from herbal production for manufacturing particleboards has been analysed, taking as examples certain herbs cultivated for the production of medicines and dietary supplements: milk thistle, marigold, and cistus. The unused parts of the herbs are considered as a potential source of raw materials for the wood-based panel industry. The stems of herbs and other post-production waste can be added to composites after appropriate treatment. A wide variety of herbs can significantly enrich the available range of composites on the global market.

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1. Introduction

In the 21st century, particular attention is being paid to environmental protection. This is achieved, among other things, through the efficient use of natural and environmentally friendly products. The European Union is placing increasing reliance on the circular economy, according to which materials should be maintained for as long as possible [1]. Agricultural and industrial activities threaten the environment and lead to climate change. This has changed the perception of natural resources as substitutes for common, poorly degradable synthetic products. Currently, dispensable and reusable dishes, straws, cloth fabrics, and other commonly used items that for decades have been made of plastic are being replaced by natural alternatives. In the case of wood-based composites, the main raw material used is wood. This has anisotropic properties, while its structure is complex [2]. It is fully renewable and biodegradable; however, constantly growing demand in the future may lead to shortages resulting from the slow recultivation of forests, measured in decades or even centuries, as well as the increasing danger of fires and awareness of the role of forests in the protection of ecosystems. The solution to these issues may be recycling or the use of other renewable raw materials, such as those from agricultural production. Innovative technologies are capable of producing, for example, wood-like panels made from straw, bamboo, or grasses.

For centuries, due to their specific properties, herbs have been used as culinary additives, in cosmetics, and in medicine. World herb production is estimated to include about 2,000 species. About 130 species classified as

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herbal plants are cultivated in Europe [3]. The total area of herb cultivation in the European Union is approximately 70,000 hectares. Poland is considered as a country with great potential in the production of herbal raw materials and their processing. Of about 2,500 plant species present in Poland, 450 are classified as medicinal plants. The herbal industry in Poland includes from 150 to 170 species [4]. Over several decades in Poland, the area of herbal plantations has decreased from 35,000 ha in the 1980s to about 15,000 ha [5] or 25,000 ha [6]. The country has about 20,000 small farms with cultivation areas between 0.5 and 2.5 ha [7]. Owing to low environmental pollution, Poland is one of the main European exporters of herbal raw materials [5]. The profitability of herb cultivation can be increased by introducing new species to the local market [8]. A characteristic feature of many herbal crops is the acquisition of a relatively small part of the plant by weight (e.g. inflorescence, seeds, fresh shoots), which on one hand necessitates the utilization of redundant remains, but on the other hand provides a possibility of cheaply acquiring and managing new sources of natural materials. Moreover, in accordance with the EU Biodiversity Strategy 2030, not less than 30% of the territories of the EU member states will be classified as protected areas, which are subject to requirements for the restoration of biodiversity. The adoption of the strategy will reduce the amount of wood available on the market, which will increase the demand for other natural resources [9].

In this article, we present an analysis of selected herbal plants – milk thistle, calendula officinalis, and cistus – in terms of their cultivation, herbal applications, chemical composition, and the possibility of using them in the production of composite boards.

2. Biodiversity Strategy 2030

The *2030 Biodiversity Strategy* is a European plan aimed at reversing the degradation of ecosystems and protecting nature by obliging Member States to take specific measures. It is an essential element of the European Green Deal, according to which by 2050 the European Union is to become a community with a circular economy and improved waste management protecting the ecosystem and biodiversity. According to the strategy, this goal will be achieved only through the close cooperation of society with its scientific communities, enterprises, and entities operating locally or nationally. Due to the emphasis on strict protection, both primary forests and old-growth forests will be defined, monitored, and protected. This is because they are the richest ecosystems that remove CO_2 from the atmosphere and are the most efficient carbon storage sites [10].

3. Methods

The Web of Science database currently contains 3,823 documents based on the keyword 'particleboard', including 3,191 articles and 521 proceedings papers. They are published mainly in three thematic areas: *Materials Science Paper Wood (1887), Forestry (990), and Materials Science Multidisciplinary (452).* In 2018 there were 222 such documents, which is currently the largest number over the years 1965–2023. Up to August 2023, 106 such documents had appeared. Figure 1 illustrates the evolution of publications on particleboard in the years 2010–2023 (Web of Science, accessed: 23 August 2023).

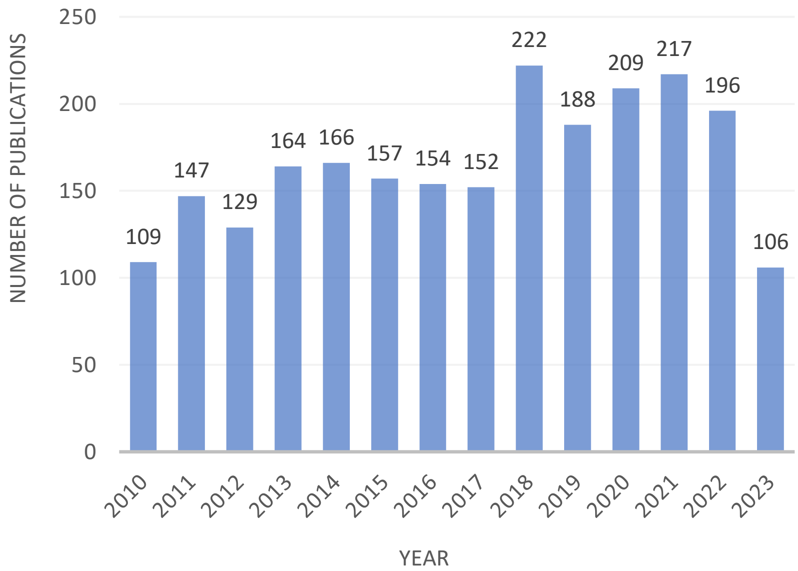


Fig. 1. Numbers of publications about particleboards in the years 2010–2023, according to Web of Science (accessed: 23 August 2023)

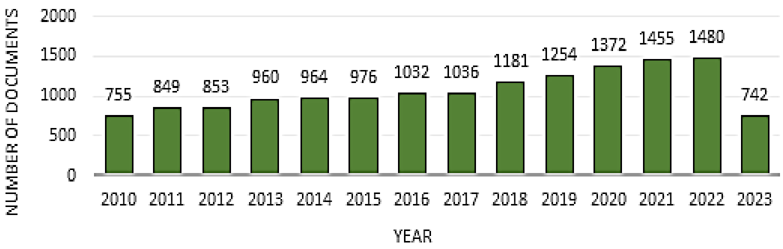


Fig. 2. Number of documents with the keyword 'herbaceous' published between 2010 and 2023 (Web of Science accessed: 23 August 2023)

The search for another leading theme of our paper, described by the phrase 'herbaceous production waste', yielded 124 publications, including 94 articles, 16 review articles, and 20 proceedings papers. The combination of the words 'herbaceous waste' gave a result of 367 documents including 308 articles, 45 proceedings papers, and 26 review articles. The overall interest in herbs is reflected in 23,009 documents with the keyword 'herbaceous' (20,465 articles, 1,638 proceedings papers, and 929 review articles) and their growing number over the last decades (Fig. 2) (Web of Science, accessed: 23 August 2023).

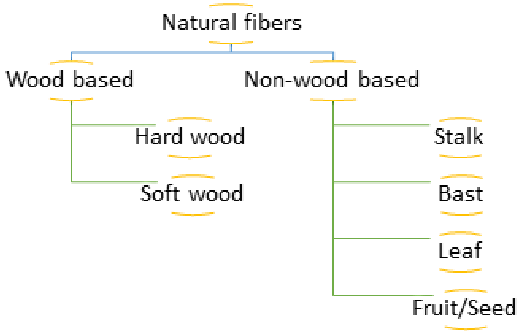
Only one article was found for the phrases 'herbaceous waste boards', 'herbaceous production waste particleboards', and 'herbaceous production waste boards', which may be an indication that this field of research and its applications remain unexplored. There is therefore a need for an assessment of the potential economic and environmental factors connected with herbal by-products.

4. Alternative raw materials for the production of particleboards

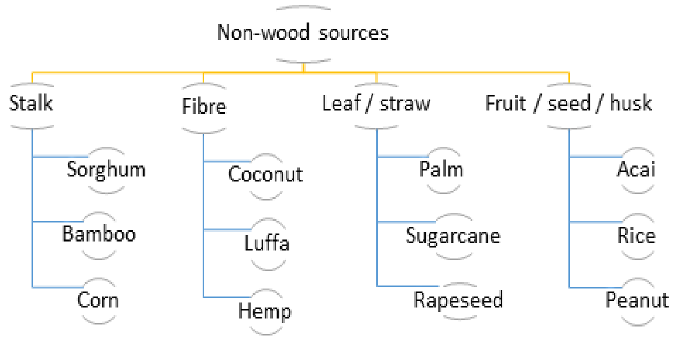
Wood-based panel manufacturers, due to the ever-changing situation with regard to wood raw materials, have begun modifying processes to enable the use of alternative raw materials such as recycled wood or other by-products of the forest industry [11]. Particleboards are made of wood chips bonded with synthetic resin or other binders, and then thermally pressed under specified temperature and pressure conditions [12]. They can also be made of various blends of lignocellulosic materials, selected depending on the intended applications and required density of the board [13], including annual plant residues, residues from garden tree pruning, or post-production residues from the food industry [14]. According to EN 309:2005, Particleboards – Definition and Classification, particleboards are classified according to surface condition, manufacturing method, shape, construction, application, and particle size and shape. Table 1 presents requirements for specified mechanical properties and thickness swelling for particleboards with a thickness range of 13 to 20 mm, which are often used as furniture boards. Due to the advantages of chipboards, they are used, among others, in the production of doors, wardrobes, home structures, and wall linings [15]. Increasing deforestation has had a significant impact on the growing demand for raw materials, which also affects the wood-based panel sector. It has generated increased interest in other sources of raw materials, including stems of various plants [16] or wooden secondary raw materials. Particleboards have also been produced using agricultural waste, for example, straw, stems, husks, or leaves [12]. Scheme 1 presents the classification of wood and non-wood natural fibres used in the production of particleboards.

Table 1. Requirements for specified mechanical properties for particleboards with a thickness range of 13 to 20 mm (EN 312:2010)

Property	Test method	Unit	Particleboard type						
			P1	P2	P3	P4	P5	P6	P7
Bending strength	EN-310	N/mm^2	10	11	14	15	16	18	20
Modulus of elasticity in bending	EN-310	N/mm^2	not applicable	1600	1950	2300	2400	3000	3100
Internal bond	EN-319	N/mm^2	0.24	0.35	0.45	0.35	0.45	0.5	0.7
Swelling in thickness	EN-317	%	not applicable	not applicable	14	15	10	15	10



Scheme 1. Classification of wood and non-wood natural fibres [17], [18]



Scheme 2. Parts of non-wood plants used in the production of particleboard [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]

Natural fibres generally display good mechanical and thermal insulation properties. Nevertheless, before committing to the use of a given raw material, its chemical composition should be analysed to determine its suitability for the production of natural composites [19].

Depending on geographical region, research on the use of alternative non-wood raw materials for the production of particleboards covers various plant species. For example, in Colombia, agricultural waste includes large quantities of cacao husks. Detailed studies of the content of chemical components of these husks has indicated the economic viability of their use for the production of particleboards [20]. In Malaysia, research is focused on the use of pseudo-fibres from banana stems as pulp, or fibres in textile products [21]. In Nigeria, scientists have investigated the possibility of using corn cobs with other raw materials such as bagasse or cassava [22], [23]. Scheme 2 presents examples of plant parts used as natural additives for the production of particleboard.

5. Worldwide production of wood-based panels in 2011 and 2021

Statistical data indicate systematic growth in the worldwide production of wood-based panels. Table 2 compares the quantities of wood-based panels produced in 2011 and 2021 (FAOSTAT, accessed: 21 April 2023).

Table 2. World production volume of selected main types of panels in the years 2011 and 2021 (FAOSTAT, accessed: 21 April 2023)

Item	Value [m³]	
	2011	**2021**
Plywood	108391,319	128729,541
Particle board	78443,536	103955,051
OSB	19914,258	37188,316
Hardboard	8709,460	7397,717
MDF/HDF	78300,123	111083,967
Other fibreboard	8874,572	7981,821

6. Herbal raw materials

Like other sectors related to plant processing, the herbal industry produces large amounts of post-production waste, which constitutes most of the harvest volume remaining after only a small percentage is used for medicinal purposes [36]. Poland is one of the largest European producers and exporters of herbal products. Some polish herbal companies produce about 30 tonnes of waste biomass per year [37]. This leads to various ideas for their use, among others in a granulation process [38], in the production of essential oils [39], in the production of polysaccharides [40] or in biogas generation [41].

To analyse the potential of herbal raw materials for use in the production of particleboard, three plants, processed in Polish herbal industry, were selected that may be potential sources of material for further research.

Milk thistle (*Silybum marianum L. Gaertn*) is an annual, rarely biennial plant [42]. It originates from the Mediterranean area, but is now cultivated around the world [43], [44]. It belongs to the Asteraceae family [45], reaching up to 2 meters in height. The stem of milk thistle is from 40 cm to 200 cm long. Its upper part is straight and branched [46], [47]. Poland is one of the most important producers of milk thistle seeds, with an area of cultivation estimated at between 1,500 and 2,000 ha [48], [49]. Milk thistle is also considered a common weed [50]. The cellulose content of milk thistle is about 33.5% of the total biomass [51], which is comparable to other herbal plants [52]. The content of hemicelluloses is low and consists only of xylans. The lignin content ranges from 13.3% to 17.1% [53]. Milk thistle is widely used as a medicinal plant [54]. The silymarin obtained from it [55], [56] is used as a hepatoprotective agent [57], [58]. Milk thistle has anti-inflammatory [59], anti-carcinogenic [55], [60], and anti-cancer effects on the skin [61]. The seeds are used, among other things, as antiviral agents [58]. Milk thistle also helps with menopausal problems [62] and growth disorders [63].

Marigold (*Calendula officinalis L.*) is an annual plant belonging to the Asteraceae family [64] originating from southern Europe [65], used as a spice or tea [66]. This plant reaches 30 to 60 cm in height [67]. In folk medicine, dried marigold flowers are used for their biologically active compounds [68]. Experiments carried out to date on marigold cultivation in Poland have focused on the inflorescences and seeds. Reports indicate that the yields of seeds vary between 1096 and 1950 kg/ha [69], [70], while the yield of flower heads in the case of fresh crops ranges from 7.87 to 38.74 q/ha, and the dry matter yield is 1.6–7.87 q/ha [71], [72]. The cellulose content in marigold is 20.8±0.6%, the content of hemicelluloses is 14.8±1.3%, and the lignin content is 24.6±1.5% [73]. Marigold is used on a large scale [74] for the production of seed oil [70]. The essential oils from the seeds are used as medicines that soothe the central nervous system [75]. Marigold has antibacterial and anti-inflammatory effects [76], [77] and it accelerates the wound-healing process [78]. It also has antioxidant properties [79]. Marigold flower is used in emollient preparations [80].

Cistus L. is a type of dicotyledonous perennial belonging to the Cistaceae family. This plant comes from the Mediterranean region. It grows in open spaces in infertile and stony soils [81]. Seasonal dimorphism has been observed in some species, which facilitates their adaptation to drought conditions [82]. The name Cistus is applied to 21 species of shrubs, most of which are characterized by a shallow root system. The height of the perennial is from 50 to 100 cm [83]. Cistus is not cultivated on a large scale in Poland [84]. The content of cellulose in the rockrose is 34.9±4.0%, while the lignin content is 15.6±0.2%, and hemicelluloses account for 6.6±3.8% [85]. Cistus species are known for their pharmacological properties [86]. In medicine, they are used to treat diabetes [87], [88], [89]. They have anti-inflammatory, antiseptic [90], hypertensive and antimicrobial properties [91], [92]. They are also widely used in skin-protecting cosmetics [93], as well as for treating burns and wounds [94].

7. Chemical composition of raw materials versus products quality

Chemically, biomass is characterized as being lignocellulosic. At a general level, the chemical composition of biomass is divided into two groups of components. The first are structural compounds that play a role in the structure of the cell wall, while the second are nonstructural components that can be removed without affecting the cell wall [95].

Cellulose is the world's most common biopolymer, and is present for example in agricultural waste, wood, and other biomass. Cellulose fibres are composed of building blocks called fibrillated cellulose [96]. Cellulose improves the mechanical properties and dimensional stability of composite products. Its content in the fibres of agricultural by-products is usually lower than in wood, flax or hemp. However, this disadvantage is offset by the lower price of the raw material, which determines many of its industrial applications [97]. Thus, for example, the lower cellulose content can be compensated for by a larger proportion in the composition, more efficient processing (e.g. higher compression), or increased thickness of boards.

Lignin is the second most abundant natural biopolymer in nature after cellulose, constituting one of the largest single sources of aromatic compounds worldwide [98], with contents of up to 30% in plant material [99]. Lignin is hydrophobic, and can affect the mechanical properties of particleboards and their biological durability [12]. It is a low-cost renewable raw material produced in large quantities every year by the wood processing, pulp and paper industries [100], and can be used for the production of semi-synthetic and natural adhesives with properties superior to those of conventional adhesives [101]. Tests carried out on lignin-phenol-formaldehyde resins have shown the positive effect of replacing phenol with lignin, which leads to improved bonding performance [102], [103].

Hemicelluloses include all polysaccharides found in plant cell walls, acting as, among other things, gluing agents [104]. They are the third major component of biomass, constituting 15–30% of the total [105]. Research has shown that the reduction of hydroxyl groups in wood, i.e. the removal of hemicelluloses, reduces moisture absorption, which increases the quality of composite products. In addition, no significant deterioration in the mechanical properties of the products was observed [106].

Table 3 compares the contents of cellulose, lignin and hemicelluloses in milk thistle, calendula and cistus with those reported in other plants. The largest content of cellulose is found in flax fibres, and the lowest in calendula remains. However, sunflower, successfully used in the natural composites industry, is the plant with the second lowest cellulose content. Of the plants compared in Table 6, the cellulose content in milk thistle is the second highest. In cistus, another herbal plant presented in this work, the cellulose content is higher than in sunflower.

Table 3. Contents of cellulose, lignin and hemicelluloses in the dry matter of selected plants. Estimated standard deviations (ESDs) are given in brackets for the last significant digits; in this notation, for example, 24.6(15) denotes an ESD of 1.5; where not given, the ESDs were not reported in the references. For milk thistle the ranges of values are listed after Tóth et al. [107]

Plant	Cellulose [%]	Lignin [%]	Hemicelluloses [%]	Reference
Milk thistle *Silybum marianum L. Gaertn*	48.49-52.05[a]	18.30(3)[b*]	4.55-4.88[a]	[51], [107]
Marigold – residues *Calendula officinalis L.*	20.8(6)	24.6(15)	14.8(13)	[73]
Cistus *Cistus L.*	34.9(40)	15.6(2)	6.6(38)	[85]
Flax – fiber *linum usitatissimum L.*	70.5	2.5	16.5	[108]
Hemp – fiber *Cannabis*	49.63	18.98	19.32	[109]
Sunflower – stems *Helianthus* L.	32.6(16)	13.3(11)	20.7(7)	[110]
Silver birch *Betula pendula* L.	47.3	19.0	28.5	[111]
Pine *Pinus*	47.4(22)	28.6(7)	21.9(49)	[112]

a [113] gives the ranges of values; b [51]

*Weighted average calculated from four different values.

8. Research on the use of herbaceous plants in the production of non-wood panels

An analysis of the available literature found several publications presenting the use of herbaceous plants for board production. Researchers from Poznan investigated the possibility of using evening primrose straw particles in combination with wood chips to produce particleboard with different binding agents, fulfilling the requirements according to the EN-312 standard [114]. Another team presented results on the use of green tea leaves as a filler in urea-formaldehyde resin for plywood production [115]. South Korean researchers determined sound absorption levels for chemically processed herbal waste applied in the manufacture of wall panels and fillers [116]. Turkish researchers indicate the potential use of conifer cones in particleboard production [117]. In Egypt, coated particle boards based on castor (*Ricinus communis* L.) steam waste have been successfully made [118].

9. Research gaps and perspectives

An analysis of the existing literature revealed several studies on the potential of using waste herbaceous plants and herbaceous production in the particleboard manufacturing process. Current research related to the processing of the above plants focuses on their health-promoting and food properties, for example, in relation to obtaining edible oils. In addition, most researchers focus on using only a certain part of the herbaceous plants, leaving a gap for research concerning the use of waste parts. Given the increase in research interest in using waste materials to produce boards , for example from agricultural and forestry waste, studies on the use of waste herbal plants should also be developed.

Summary

In this paper we have reviewed applications of the waste parts of selected herbal plants. These parts can be valuable raw materials for the production of panels. Our analysis indicates that there are real possibilities of utilizing these plant remnants for producing natural composites and extending the range of natural conventional products available for use. Over the past ten years, interest in wood-based panels has increased significantly. Considering the increase in the use of wood, which is fully biodegradable but slowly renewable, there should be a focus on the possibility of using other natural resources, including plants that are not fully processed, such as herbal plants like milk thistle, marigold, and cistus. The location of herbal processing plants and arable fields in Poland and in other countries may be a logistic advantage, reducing the cost of transport. This not only has a practical dimension, but can also reduce the associated carbon footprint. The development of a local market will also mean an increase in revenue for farmers selling unused plant parts, and will minimize waste disposal costs for growers of herbal plants by enabling the waste to be sold or transferred to companies that use it in the production of boards. European producers of wood-based materials, in addition to offering new products and increasing their sales and profits, will also be eligible to apply for financial support from EU funds dedicated to research on the introduction of "green" innovations in the marketplace. In order to determine the suitability of herbal plants for the production of composites, tests should be carried out, including the production of boards based on the herbal plants presented in this work and investigation of their mechanical properties, formaldehyde content and emission, flammability, and other technological and functional parameters. The constantly evolving approach to recycling and environmental protection increases the need for new concepts regarding the use of waste for producing goods and raw materials, particularly those in demand in the construction sector.

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