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Review

Utilization Potential of Tree-of-Heaven Species Biomass—A Review

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Abstract: Climate change and the subsequent increase in global mean air temperature already present a significant impact on forest vegetation. Especially in the near future, several forest species are expected to be in danger of extinction or compelled to migrate to colder regions. Some common species will be replaced by highly climate-tolerant species, primarily exotic plants, among others. The tree of *Ailanthus*, or "tree-of-heaven", as it is widely known, constitutes a rapidly growing plant, considered to be native to parts of China, while since the middle of the 18th century, it gradually spread to Europe and North America. This species demonstrates a preference for warmer, drier environments, although it can also survive in a variety of habitats and endure pollution of urban areas. It is a species with several uses, such as for animal feed, fuel, timber, pharmaceutical applications, etc., while its suitability for specialized applications of high-added-value is constantly being investigated. Its wood has a desirable appearance and characteristics that are comparable to those of other hardwood species of similar densities/weight. This article discusses some of the most important characteristics of *Ailanthus* wood and presents a comprehensive and constructive review of the chemistry, pharmacology, traditional and innovative uses, quality control, biological resistance, potential utilization in bioenergy and biofuels and wood products (e.g., wood-based panels, other advanced structure materials, etc.), use challenges and limitations, in order to contribute to the utilization potential assessment of this species biomass.

Keywords: *Ailanthus*; biofuels; biomass; chemical composition; fast growing; invasive; mechanical strength; pulp; waste; wood

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1. Introduction

Global warming is evidenced mainly by rising global mean air and ocean temperatures, extensive melting of snow and ice, and rising global mean sea levels. A layer of greenhouse gases mostly made of water vapor, in far lower amounts, carbon dioxide, methane, and nitrous oxide act as a thermal blanket around the Earth, absorbing heat and concurrently heating its surface to temperatures suitable for the growth of living creatures. Several experts declare that the "greenhouse effect" caused by human activity is mostly responsible for the current trend of global warming. As the main contributor to climate change, CO_2 is a rather small but significant part of the atmosphere. It is created by both natural processes, such as respiration and volcanic eruptions, and human activities, such as deforestation, land use changes, and fossil fuel burning [1,2].

Simulations of future vegetation distribution in the European area indicate that by the end of the century, at least one-third of the land surface area may be covered by different vegetation species [3]. Changes in the plant species are likely to be considerably more significant in southern Europe, with widespread replacement of forest by shrubland predicted, owing mostly to drier conditions and catastrophic impact of fire [4,5]. Only a few locations in Greece appear to have a process-based projection study of how forest ecosystems would adapt to climate change [6]. These simulations appear to support the overall trend of elevation changes in species distribution and the replacement of drought-sensitive species with drought-resistant ones, with favorable interactions with the local environment.

In parallel, the global demand for fibrous lignocellulosic materials coming from wood industries is constantly rising, while the production of industrial wood of high quality obtained from natural forests continues to decline [1]. The deficit of forest products in developing countries is mainly attributed to the depletion of forest resources due to deforestation, human intervention, institutional failure, etc. [2], while in developed countries, it is attributed to the reduction of forest areas intended for industrial wood production (versus other uses such as recreational areas, etc.) [7]. The remaining forests experience high pressures due to the higher demand for wood in the forest industry attributed to the ever-increasing population and new application areas [8].

In order to be able to meet future material and wood demands and overcome the existing wood shortage, studies have so far focused on the utilization of alternative and competitive materials in forest industries, especially as raw materials for the production of sawn wood, pulp, paper, biofuels, and other products [1,9,10]. The answer to the timber shortage problem could possibly be partly provided by the cultivation of some fast-growing, short-rotation species.

In recent years, many countries have focused their attention on the utilization of wood derived from species that are considered undesirable in natural ecosystems and are classified as invasive or pests (*Ailanthus altissima*, *Robinia pseudacacia*, *Ambrosia artemisiifolia*, etc.) because of their tendency to spread at such a rapid rate and to such an extent that they suppress native vegetation species. Such species have not been properly utilized in appropriate applications to date [11].

Ailanthus species, commonly known as tree-of-heaven (Figure 1), has concerned many studies around the globe, although so far, according to the literature, there is not enough information concerning its properties towards its extensive and successful use in a multitude of applications (wood-based products, composite materials, chemical products, biofuels, etc.). The properties and characteristics of this fast-growing species, which remains underestimated until now, should be thoroughly investigated in order to promote the production of high-added-value products utilizing such a low-quality and low-cost raw material.

Figure 1. *Ailanthus altissima* species.

A. altissima is a deciduous tree that is native to China, though it has become naturalized in many parts of the world, including North America, Europe, and Oceania. It constitutes a member of the *Simaroubaceae* family and is one of the five species of the genus *Ailanthus* Desf. The genus *Ailanthus* comprises about 10 species, which are native to Asia and northern Oceania. *A. altissima* was named by Swingle in 1916 [12]. Three varieties are recognized, vars. *Altissima, tanakai*, and *sutchuensis* [13]. Several other varieties have also been described. Apart from *A. altissima*, its congeners are *A. excelsa* Roxb., *A. Integrrifolia*

Lam., (including *A. calycina Pierre*), *A. triphysa* (Dennst.) Alston, [12,14]. In the research implemented by Saina et al. [15], the phylogenetic analysis using protein-coding of the genes revealed that *A. altissima* is genetically related to *Leitneria floridana*, as well as the family *Simaroubaceae* to the family *Rutaceae*. The word "*Ailanthus*" is derived from the Moluccan name "aylanto", which refers to the native *Ailanthus integrifolia* and means "tree of heaven". The word "*altissima*" means very high. Some other scientific names of the species are *Ailanthus cacodendron* (Ehrh.) Schinz and Thell, *Ailanthus giraldii* Dode, *Ailanthus glandulosa* Desf., *Ailanthus peregrina* (Buchoz) F. A. Barkley, *Ailanthus sutchuensis* Dode, *Ailanthus vilmoriniana* Dode, *Albonia peregrina* Buchoz, *Pongelion glandulosum* (Desf.) Pierre, *Rhus cacodendron* Ehrh., *Toxicodendron altissimum* Mill.

It is a highly adaptable species that is able to grow in a wide range of environmental conditions, including disturbed sites, urban areas, and forest edges. *A. altissima* presents both positive and negative ecological impacts. It can provide habitat for several wildlife species and has been used in traditional medicine, though it is also considered a highly invasive species that could displace native vegetation and reduce biodiversity. Its allelopathic effects can inhibit the growth of other plant species, and it can also release allelopathic compounds (allelochemicals, mainly quassinoids, including ailanthone, ailanthinone, and ailanthinol, chaparrinone, chaparrin, shinjudilactone, shinjulactone, etc.), contained mainly in the root bark and other parts of the plant, into the soil, affecting soil microbial communities and nutrient cycling. Management of *A. altissima* can be challenging, mainly due to its fast growth, ability to resprout from roots and cut stems, and its prolific seed production. Controlling methods include mechanical removal, chemical treatments, and the use of biological agents, although each has its own limitations and potential drawbacks [11].

The aim of this review is to identify, appraise, and synthesize all the evidence available so far on the biology, ecology, distribution, impacts, management, and utilization options, and potential of *A. altissima*. This review, dealing with this species' biomass, would undoubtedly provide a comprehensive and structured overview of the available literature and help identify research gaps and priorities for future research and management efforts.

2. Nature and Characteristics of *A. altissima*

2.1. Ecology and Distribution of *A. altissima*

A. altissima is a deciduous tree with a wide range of ecological tolerances, including tolerance to drought, pollution, and a variety of soil types. It is a fast-growing, climate-tolerant species that prefers warmer and drier environments, although it can also survive in a variety of habitats of a wide temperature- and air humidity-range, while it seems to withstand drought, using a highly effective mechanism for saving water with reduced water loss from leaves and reduced root hydraulic conductivity [12]. It is noticeable that in several regions of Asia with harsh and adverse climatic conditions and poor soils, this species holds a key role in the local economy and is characterized as a kind of multiple-purpose species.

It reproduces both sexually and asexually, with the latter being the main mechanism of spread [12]. This tree species can reach up to 25–30 m in height and has a distinctive appearance, with smooth gray-brown bark, large pinnate leaves, and clusters of small yellow-green flowers that develop into samara fruit. *A. altissima* has both dioecious and hermaphroditic forms, with male and female flowers produced on separate trees, while hermaphroditic flowers are produced on the same tree.

It can rapidly colonize disturbed areas and form dense thickets, competing with native vegetation. The tree has been found to exhibit allelopathic effects, releasing compounds that can inhibit the growth of other plant species. Allelopathy is the ability of a plant to release chemicals that inhibit the growth of other nearby plants. It also has a high level of insect herbivory, with several species of insects feeding on the tree's leaves, stems, and fruits [12,16,17].

Nowadays, it can be found in many parts of the world, including Europe, Asia, Africa, and North and South America. Distribution data for *A. altissima* can be collected from several global databases, such as (A) the Global Biodiversity Information Facility (GBIF),

(B) Centre for Agriculture and Biosciences International (CABI), (C) the Global Invasive Species Database (GISD), and (D) Delivering Alien Invasive Species Inventories for Europe (DAISIE). Espenschied-Reilly and Runkle [18] investigated the distribution and changes in abundance of *A. altissima* (Miller) Swingle, in a southwest Ohio woodlot. The study involved sampling of *A. altissima* population in a 12.6-hectare woodland from 1978 to 2006. It was concluded that this species was present in the study area throughout the study period, with a high initial abundance and a subsequent decline in population density over time. This decline in population density could be attributed to natural factors, such as competition with other species or mortality due to disease or insects. It was also revealed that it was most abundant in disturbed areas of the woodland, such as along the edges and in degraded areas that had been previously logged or cleared. Generally, this species is commonly found in disturbed habitats, such as roadsides, vacant lots, and abandoned fields. It can also invade natural ecosystems and outcompete native plant species [12]. The tree produces an extensive root system that can contribute to its ability to grow in a wide range of environmental conditions, including nutrient-poor soils and areas with high levels of pollutants [19]. It was suggested that the species has a high capacity for colonizing disturbed habitats, and its presence in the study area could be attributed to previously applied land-use practices [18].

Brusa and Holzapfel [20] investigated the population structure of the invasive tree species *A. altissima* and the role of land-use history and management practices in shaping its distribution. The study was conducted in an urban area of northern Italy and involved sampling 37 populations of this species across different land-use types. The importance of land-use history and management practices is highlighted by the researchers in shaping the distribution and population structure of *A. altissima* species. The results showed that this species was present in all land-use types, with a higher frequency in disturbed habitats such as abandoned areas and industrial sites. The genetic diversity of the populations was found to be high, indicating the high potential of this species for adaptation and evolution. This genetic diversity could be explained by its ability to rapidly colonize disturbed habitats and its high speed of growth. The seedlings often grow 1–2 m in their 1st year and the tree may reach a 20-m height and a 1.5-m diameter in 10 years [21,22].

It has a complex genome with an estimated size of 1.5 Gb. The genome has been sequenced and annotated, providing insights into the genetic basis of the tree's growth and development [12].

Overall, further research is necessary to fully comprehend the biology of *A. altissima*, including its genetic diversity, physiological adaptations to different environments, and interactions with other species in order to assist management strategies application concerning the control of this invasive species' spread and minimize its impact on native ecosystems [11].

2.2. Management of A. altissima

Various management strategies have been developed to control the spread of *A. altissima*, including physical, chemical, and biological control methods. Physical control methods include cutting, pulling, and girdling the tree. Chemical control methods involve the use of herbicides. Biological control methods involve the introduction of natural enemies, such as insects and fungi.

More specifically, Pisuttu et al. [23] investigated the physiological and biochemical responses of this species to the infection by the soilborne fungal pathogen, *Verticillium dahliae*. *V. dahliae* was found to cause significant damage to the leaves, roots, and stems of *A. altissima*, which resulted in reduced growth and biomass production. The infected plants also showed alterations in their antioxidant defense system and photosynthetic pigments, indicating oxidative stress and impaired photosynthesis. The study provided insights into the mechanisms underlying the decline of *A. altissima* under biotic stress and highlighted the potential of *V. dahliae* as a biological control agent against this invasive plant species.

Brusa and Holzapfel [20] revealed that management practices, such as cutting and herbicide application, were effective in reducing the density of this species populations, though the method did not eliminate the species. The researchers suggest that long-term management strategies that involve a combination of different control methods may be necessary to effectively manage its spread. Espenschied-Reilly and Runkle [18] declare that management practices that involve reducing the disturbance of the forest ecosystem and promoting the growth of native species could be effective in controlling its spread.

Nunes [24] discussed the creation of value chains to support sustainable control and eradication actions on *A. altissima*. They presented a theoretical framework for value chain creation and identified potential stakeholders and their roles in the process. They also highlighted the economic, environmental, and social benefits that can be derived from the sustainable management of this species, such as the production of biofuels [25–27], animal feed [28–30], and other value-added products [31]. Jat et al. [29] also characterized *Ailntahus* as a multiple-purpose, compatible species, stating that its leaves, bark, and residual biomass can be used, among other uses, as animal feed, combating drought and securing livelihood security of resource-poor people. Ganai et al. [30] concluded that harvested green *Ailanthus* leaves contained 18.22% CP, 4.40% EE, 15.79% CF, 50.04% NFE, 26.60% NDF, 18.10% ADF, 8.50% hemicellulose, 5.11% ADL, 11.41% TA, 1.98% Ca and 0.27% P in dry matter, are palatable, extremely delicious, and nutritious feed for sheep and goats that contribute to the health of animals. The creation of value chains could be a viable strategy for addressing the negative impacts of *A. altissima* on ecosystems and promoting sustainable development in affected regions.

2.3. *Ailanthus altissima Biomass Chemical Analysis*

A. altissima leaves and bark have been found to contain various extractives, mainly essential oils, that have antimicrobial and antioxidant properties. These extractives contain various chemical compounds, including sesquiterpenes, monoterpenes, and phenols, several alkaloids, including quassin, ailanthone, and ailtirone [30]. These alkaloids have been found to have insecticidal and antifungal properties [31]. Especially the bark contains a variety of bioactive compounds, including alkaloids, flavonoids, and terpenoids, which may contribute to its medicinal properties. The pharmacological properties of *A. altissima* bark, including its anti-inflammatory, analgesic, antioxidant, antimicrobial, and anticancer effects, have also been highlighted [32]. Kalaskar et al. [33] reported that the stem bark of *Ailanthus excelsa* Roxb is rich in phenolic compounds, known for their antioxidant and anti-inflammatory properties, and may have potential as a source of natural antioxidants and as a natural preservative in food and cosmetic industries. Extracts from leaves have even greater phenolic content than the other parts of this species tree, and a positive linear correlation between antioxidant activity and total phenolic content of all the extracts has been reported [34]. Further studies are necessary to evaluate the safety and efficacy of using this species in food and cosmetic products.

Ailanthone, which constitutes an extractive of this species, can be utilized for the production of various unique and valuable products (pharmaceuticals, herbicides, insecticides, and ecological products). Its leaves have been found to contain various flavonoids, including kaempferol and quercetin. These flavonoids have antioxidant and anti-inflammatory properties. *A. altissima* bark has been found to contain tannins, which have astringent properties, and coumarins that demonstrate anticoagulant properties and are employed in the treatment of various medical cases [32].

Caramelo et al. [35] described that the main extracts for analyzing the biological activities of *A. altissima* are essentially obtained from the leaves, seeds (e.g., essential oil), and bark. However, extracts from other plant parts, such as flowers and stems, have been rarely investigated.

Chuang et al. [36] investigated the biosynthesis pathway of the bioactive compounds of quassinoids in the invasive tree-of-heaven and confirmed their evolutionary origin from protolimonoids. This study contributed to the development of potential applications in the pharmaceutical and agricultural industries. Transcriptome sequencing and gene expression analysis were employed to identify the genes involved in the biosynthesis of quassinoids in this species. Thirty genes involved in the biosynthesis of quassinoids were identified, including several genes that are responsible for the formation of protolimonoids, which are the precursors to quassinoids. These findings could potentially lead to the production of new bioactive compounds with diverse biological activities, with applications in the pharmaceutical and agricultural industries, although further research is needed to explore these possibilities.

Pettersen [37], analyzing *Ailanthus* species from the Caucasus region, reported 46% cellulose, 14% lignin content, and 0.9% ash content. Demirbas [38] reported 26.6% hemicelluloses content, 46.7% cellulose, 26.2% lignin, and 0.5% ash content. Samariha and Kiaei [39] identified that in the wood trunk of this species, the cellulose content was 47.18%, which is suitable for pulp production, lignin 25.19%, extracts, 3.5%, and ash 1.25%, while in the branch wood, the percentages of cellulose were 44.12%, lignin 23.86%, extracts 3.2%, and ash 1.75%. Lignin was higher in the trunk compared to the branch by 5.3%. Furthermore, Hosseinzade et al. [40] found the lignin content in the trunk to be 25.19%, while Talaeipour et al. [41] found 23.33%, respectively. A difference in the amount of extract content was recorded between the stem and branch by 8.6% [41].

Saidur et al. [42] recorded 26.60% hemicelluloses content, 46.70% cellulose, 26.20% lignin, and 0.5% ash content, which chemical composition corresponds to a heating value of 18.93 MJ/kg. Rahman et al. [43] also found high levels of lignin (25.84%) and extractives (8.3%), such as phenolic compounds, flavonoids, and terpenes, and recorded quite low ash content, indicating that it could be suitable for use as a biofuel.

Bardak et al. [44], in the chemical analysis, carried out on the wood of *Ailanthus* grown in the Trabzon area, reported 49.8% cellulose, 29.1% hemicelluloses, 21.3% lignin, and 0.21% ash, while in the respective wood from Artvin area, the results showed 46.5% cellulose, 24.4% hemicelluloses, 24.9% lignin, and 0.35% ash. Terzopoulou and Kamperidou [32] chemically characterized the wood and bark of *A. altissima* originating from three different locations in North Greece, with a focus on the horizontal variability assessment of its chemical composition (Table 1). Significant differences were found in the chemical composition of biomass obtained from these different locations. Furthermore, bark presented higher extractive content, slightly higher lignin content, much higher ash, and slightly lower holocellulose content than wood. As the tree age increased, the wood and bark presented lower lignin, though a linear increase of holocellulose and extractives contents. Additionally, the heartwood demonstrated higher extractive content, lignin and ash, and lower holocellulose content than sapwood.

Küçük and Demirbaş [45] investigated the kinetics of the hydrolysis of *A. altissima* chips using an alkaline-glycerol solution and highlighted that the hydrolysis rate increased with increasing temperature, biomass concentration, and alkaline concentration.

Table 1. Findings of *A. altissima* chemical analysis.

Study/Source	Part	Extractives (%)	Lignin (%)	Holocellulose (%)	Ash (%)	Applications
Pettersen [37]	wood	-	14	46	0.9	
Khattak et al. [46]	wood	19.89 Alcohol-Benzene 18.6 hot water	22.19	80.12	-	pulp-paper
Demirbas [47]	wood	--	26.2	46.7	0.5	
Samariha and Kiaei [39]	stem branch	3.5 3.2	25.19 23.86	47.18 44.12	1.25 1.75	pulp-paper
Saidur et.al. [42]	biomass	-	26.2	46.7	0.25	-
Bardak et al. [44]	wood	--	21.3	49.8	0.21	-

Table 1. *Cont.*

Study/Source	Part	Extractives (%)	Lignin (%)	Holocellulose (%)	Ash (%)	Applications
Terzopoulou and Kamperidou [32]	latewood 10 y.o	7.2	33.2	73.3	0.6	-
	latewood 3 y.o	7.5	32.5	72	0.7	-
	latewood 30 y.o	8.7	41.8	63.3	0.8	-
	earlywood 10 y.o	10.9	36	75.3	0.8	-
	earlywood 3 y.o	8.1	41.3	73.9	0.8	-
	earlywood 30 y.o	12.6	40.7	59.6	0.8	-
	bark 10 y.o	17.7	43.5	56.4	4.3	-
	bark 3 y.o	17.3	39.2	62.8	4.7	
	bark 30 y.o	26.9	36.4	56.8	4.5	

2.4. Structural and Physical Properties of A. altissima Wood

Understanding the physical properties of *A. altissima* wood is also important for the determination of its suitability for different applications. The density of wood is reported to range from 0.46 to 0.72 g/cm^3, depending on the specific growth conditions and location [48,49]. This species is classified as a medium-weight woody species. The estimation of the density of a wood species constitutes valuable information for the evaluation of wood quality and its proper utilization.

The wood of *Ailanthus* is ring-shaped, white-yellowish, of smooth texture. The vessels of the late wood of this species are rather sparse, 170–250 µm in width, with simple perforations and smooth walls containing marginal cavities. Vessels in early wood are spiral and occur in clusters of 80–150 µm width [50]. The vessels are attached to the tracheids and are reinforced in spirals, where parenchyma also develops around the vessels. The rays of the wood core consist of several rows (5–7 cells). These cells have thin walls with many cavities, are 8–15 µm high, and the peripheral ones up to 32 µm. Arnaboldi et al. [51] reported that the wood of *Ailanthus* has a characteristic high porosity on the surface of the vessels, similar to oak and chestnut. In contrast to these two species, vessels in *Ailanthus* wood are grouped in 2–3 and only occur in the early wood. In the late wood, axial parenchyma cells are visible, where they tend to form bundles, and their arrangement does not depend on the vessels. Concerning the morphological characteristics of this species, studied by Kúdela and Mamoňová [52], the mean diameter of the early wood vessels was found to be 230 µm, which is in agreement with the value obtained by Balaban [53], and the length was found to be 259 µm, while in the late wood, the mean diameter of the vessels was 41 µm and the length was 369 µm, and the mean fiber length was 939 µm. The vessels in the early wood occur singly, but they are also found in two or three groups. The thin cell walls contain many cavities. The diameter of the vessels in the early wood is high, the vessels in the late wood appear in groups, and have thin walls. the axial parenchyma, is concentrated near the late wood cells, which are reinforced by threading, and finally, the core rays are most often composed of five rows. In general, the wood of *Ailanthus* is considered hard, of medium weight, difficult to split, and easy to bend. However, Demeter et al. [54] evaluated the physical properties of *Ailanthus* wood grown in different regions of India and reported that the wood had a low density, high porosity, and moderate strength properties, making it suitable for lightweight construction applications.

Porosity, however, is mainly associated with the quantity of vessels in the early wood, the number of which is about twice higher in the transverse and sapwood. Latewood cells are much less permeable to water than vessels. In addition to the quantity of vessels, their quality is an important factor. Based on cell anatomy, this species can contain a high amount of water and thus resist extremely dry conditions [52]. Li et al. [55] reported that the density, modulus of elasticity, and modulus of rupture of *Ailanthus* wood were found to be decreased as the moisture content increased.

The factors influencing the density of wood are the amount of water contained in the wood mass, its structure, and the main chemical composition of the wood (extractives, cellulose, hemicelluloses, lignin, etc.) in terms of linear and volumetric swelling. The mean swelling in the radial direction is 4.1% and classifies the wood as a wood species with low swelling. Based on the values of swelling in the tangential direction (10.8%) and volumetric swelling (16%), this species is classified as a wood species of moderate swelling [48]. Nevertheless, Li et al. [55] marked a high level of shrinkage and swelling and, therefore, poor dimensional stability.

Overall, the physical properties can vary depending on factors, such as location, moisture content, and processing. Danihelová et al. et al. [56] marked high sound velocity and acoustic stiffness, making *Ailanthus* species wood suitable for use in musical instruments, as well as a low density and moderate mechanical properties, making it suitable for lightweight construction applications. Merhar et al. [57] investigated the machinability of the most common invasive tree species in Slovenia, including *A. altissima*, *Robinia pseudoacacia*, and *Acer negundo*, which cause significant ecological damage and economic losses, and reported especially for *A. altissima* that it is relatively easy to be machined and can be processed using standard simple woodworking equipment.

2.5. Mechanical Properties of A. altissima

According to the literature, tree-of-heaven wood is characterized by satisfying mechanical properties, especially for its weight [50]. Merhar et al. [57] marked relatively low density and strength and considered this species less suitable for certain applications, those of high strength requirements. It presents a very high increase in strength after drying. Özçifçi and Hiziroglu [58] recorded lower modulus of elasticity (MOE) and modulus of rupture (MOR) than other hardwood species, such as oak and beech, as well as a lower density than these hardwoods. Li et al. [59] attributed the quite low MOE and MOR to the presence of extractives, such as tannins, although the presence of these extractives could improve the durability and resistance of wood to decay, as well as to the presence of lignin. In general, the MOE has been reported to range from 7.2 to 17.1 GPa, while its MOR wood has been reported to range from 50.5 to 91.2 MPa (Table 2). A more recent study by Olsson et al. [60] evaluated the mechanical properties of this wood species untreated and treated with a soybean oil-based resin. The results showed that the treated wood demonstrated improved MOE and MOR compared to untreated wood, indicating that the resin treatment had reinforced the wood. Of course, the stress and strain values of *A. altissima* wood vary depending on the specific growth conditions (age, growth rate, etc.), origin, and environmental conditions, as well as the testing methods used, and other factors such as density, structure, extractives and treatment applied [61]. Although its wood may not have similar or superior mechanical properties compared to other valuable hardwoods, it could still be considered suitable for certain applications where the weight, biological durability, or acoustic properties are of important consideration.

Table 2. Mechanical and physical properties of *A. altissima* wood.

Ref.	Density r10 (g/cm^3)	Shrinkage (%)	Axial Compression Strength (N/mm^2)	MOR/(Bend. Strength) (N/mm^2)	MOE/(Bend. Strength) (N/mm^2)	Impact Bending Strength (J/cm^2)	Hardness Radial (N)	Hardness Tangendial (N)
Požgaj et al. [62]	0.658	-	-	-	-	-	-	-
Moslemi Bhagwat [63]	0.531	10.81	36.3	81.5	10,492.41	3.94	7702	6839
Kúdela and Mamoňová [52]	0.545	16.00	-	-	-	-	-	-
Panayotov et al. [64]	0.62	14.85	55.83	71.11	11,906	-	4407	5407
Miao et al. [65]	0.638	16.2	110.9 axial	148.3	-	-	-	-
Barboutis and Kamperidou [66]	0.6	-	64.47	101.29	10,259.31	3.811	5687.8	5141.5
Medved et al. [67]	0.555	-	-	-	-	-	-	-
Szabolcs, and Varga [68]	0.653	-	53.4	111.07	11,665	6.11	-	-

2.6. Uses of A. altissima

This species could be used to meet many requirements of modern civilization. Widespread use in the past has demonstrated many successful applications in several fields. In China, it was mainly used in traditional folk medicine [69]. Extracts obtained from the bark of *Ailanthus* have been used in the past to fight diarrhea and dysentery. Extracts from the root of the species have been used to treat epilepsy, asthma, and fever. According to the literature, extracts of the fruit have been used to treat eye diseases and also as an astringent. In sprayed form, it seems to contribute to seborrhea and in the treatment of psoriasis [12]. Research has been carried out on its pharmacological effects [70], as well as on the detection of compounds with antiproliferative, cytotoxic, and antiviral action [70]. *A. altissima* seeds are a source of fatty oils and proteins. The oil is aromatic and bitter, though it can be used after refining [71]. Researchers believe that the extractives contained in *A. altissima* may have certain positive effects against cancer cells [70]. Additionally, Zhu et al. [72] reported the isolation and characterization of two new tetracyclic triterpenoids, called ailantinols A and B, obtained from the fresh bark of *A. altissima*. The authors also evaluated the potential cytotoxicity of the compounds against several human cancer cell lines and found that ailantinol B showed moderate activity against two of the tested cell lines.

Gürbüz and Kahramanoğlu [73] suggested that *A. altissima* leaf extracts can be used as a natural alternative to synthetic preservatives for maintaining the postharvest quality of fresh apricot fruits and that the leaf extracts favor the quality and shelf life of fresh apricot fruits by delaying the ripening process and reducing weight loss during storage. Leaf extracts were found to have a high content of phenolic and flavonoid compounds and exhibited significant antioxidant activity. However, further research is required to evaluate the safety and efficacy of using these extracts on a larger scale in the fruit industry. The study of Kim et al. [74] suggests that *A. altissima* leaves extract in lipopolysaccharide (LPS)-stimulated astrocytes has anti-inflammatory properties and may have therapeutic potential in treating neuroinflammatory diseases. Specifically, they found that the extract reduced the production of reactive oxygen species (ROS) and inhibited the activation of nuclear factor kappa-B (NF-κB) and mitogen-activated protein kinases (MAPKs) signaling pathways. However, the mechanisms of action should be further explored.

Andonova et al. [75] investigated the phenolic profile, antioxidant and DNA-protective capacity, and microscopic characteristics of aerial substances of *A. altissima* and showed that the aerial parts of this species are rich in phenolic compounds and have strong antioxidant and DNA-protective activities.

Its foliage has been used for silkworm breeding, and its wood as a material for various constructions [61] and traditionally as firewood, although the use as wood-based material applications will be analyzed in the following. Talaeipour et al. [41] revealed a high utilization potential of wood and branch material of this species for paper and wood pulp production.

The species has been introduced to various parts of the world as an ornamental one in urban environments, attributed to its resistance to pollution and its ability to act as a herbicide and repel native insects, it has replaced other, more sensitive, species such as ash (Tilia sp.) [12]. Limited literature has been detected concerning the use of *A. altissima* as a herbicide, although some research has been conducted on the allelopathic effects of the species on other plants [34].

It has been found that extracts of *A. altissima* leaves and roots inhibited the germination and growth of several plant species, including lettuce, radish, and tomato [76]. The researchers identified several chemical compounds in the extracts, including quassinoids, which are known for their allelopathic impact. Bajwa et al. [76] suggested that this species extract could be used as a natural herbicide to control the growth of weeds.

Galatowitsch et al. [77] found that the presence of *A. altissima* had a negative impact on the growth and survival of several native plant species in a riparian ecosystem. The authors investigated the invasiveness of wetland plants, including *A. altissima*, in temperate North

America and suggested that these findings could have implications for the management of wetland ecosystems and that efforts to control the spread of this invasive species may be necessary to maintain native plant biodiversity. This study indicated that the allelopathic effects of this species may contribute to its invasiveness and ability to outcompete native species.

Furthermore, Novak et al. [78] investigated this species' root extracts and isolated ailanthone allelopathic effects on the growth of three test species (lettuce, radish, and cress) in laboratory conditions. They used different concentrations of root extracts and isolated ailanthone to test their effects on the germination, root and shoot growth, and biomass accumulation of the test species. The results showed that both the root extracts and isolated ailanthone had allelopathic effects on the test species, but the effects varied depending on the concentration and the test species. The highest concentrations of root extracts and especially the isolated ailanthone significantly reduced the germination and growth of all test species, while lower concentrations had no significant effects or even promoted the growth of some species. The authors suggested that the allelopathic effects of tree-of-heaven on other plants could be attributed to various allelochemicals, including ailanthone.

Kozuharova et al. [79] explored the potential of the invasive plant *A. altissima* as a source of natural pesticides. They reported that the plant has a high content of biologically active compounds, including alkaloids, flavonoids, and tannins, which have shown insecticidal and fungicidal properties. The study included a comprehensive assessment of the phytochemical composition and biological activity of different parts of *A. altissima*, including leaves, stems, and seeds. They reported that the plant extracts showed strong insecticidal and fungicidal properties against various pests and pathogens, including aphids, spider mites, and powdery mildew, and also discussed the economic potential of this species as a source of natural pesticides. It was suggested that the development of a sustainable and eco-friendly production chain for this species' extracts could provide new opportunities for rural development and job creation.

Hopson et al. [80] examined the physiological and transcriptomic responses of *Arabidopsis thaliana* to ailanthone, as a potential bio-herbicide and analyzed the effect of different concentrations of this substance on the growth, chlorophyll content, and gene expression of *Arabidopsis*. The results showed that ailanthone had a dose-dependent effect on *Arabidopsis* growth and chlorophyll content. At higher concentrations, ailanthone inhibited the growth and chlorophyll content of *Arabidopsis*. Several differentially expressed genes in *Arabidopsis* were identified as a result of the exposure to ailanthone, and these genes were involved in various biological processes, including stress response, cell wall modification, and hormone signaling pathways. Light was shed on the action mechanisms of this compound on plant physiology and gene expression. However, the effects of ailanthone on other plant species have not been detected so far, or on the potential environmental impact of using this compound as an herbicide. Therefore, further research is needed to explore the potential efficacy and safety of using ailanthone as an herbicide and to assess its environmental impact.

Although these studies suggest that *A. altissima* may have potential as a natural herbicide, it is important to keep in mind that the species is still considered invasive and has negative impacts on native ecosystems. Using this species extracts as an herbicide or insecticide could potentially harm non-target plant species and contribute to the spread of this invasive species. Further research is needed to fully comprehend the potential risks and benefits of using *A. altissima* as an herbicide [81]. There are many alternative methods for pest control, including integrated pest management techniques that focus on prevention, monitoring, and the use of environmentally friendly methods [82].

Among several other uses, this species is also valued for the shade it provides and erosion control, particularly in cities where soils are poor, and the atmosphere is polluted [19,83]. In particular, since 1950 and onwards, several plantations of *A. altissima* have been established in different parts of Europe in order to protect barren, steeply sloping, and eroded soils on slopes and on soils disturbed after a mining activity. It has also been used in the rehabilitation of landfills [83]. In the Czech Republic and Hungary, it has been used towards afforestation and reforestation, and in some areas, it has also been used for honey production [12].

Mohebzadeh et al. [84] investigated the effectiveness of *A. altissima*, and organic amendments in remediating heavy metal polluted soil. The study was carried out in a greenhouse and involved four treatments: Control (untreated soil), organic treatments only, plant species only, and a combination of organic treatments. The concentrations of heavy metals (Cu, Zn, Pb, and Cd) in the soil were measured before and after the treatments. The results showed that this species was able to accumulate heavy metals in the tissues and that it is more effective in accumulating Cu and Zn. Organic treatments alone did not significantly affect heavy metal concentrations in the soil or plant. However, the combination of organic amendments and plant species resulted in a significant reduction of heavy metal concentrations in the soil, indicating that the two remediation strategies could work synergistically. Further research is needed to investigate the long-term effects of these treatments on soil health and plant growth.

According to Terzopoulou and Kamperidou [32], very low ash contents and high calorific values proved high potential for utilization in solid biofuel production. The optimum harvesting time for the highest possible utilization of extractives and holocellulose is after the 21st year of the tree, while for lignin, after the fifth year of the tree. Of course, for qualitative timber utilization, trees should be harvested before the age of 30 years since, in older trees, the wood begins to degrade [19].

2.7. Utilization of *A. altissima* Biomass in Wood-Based Products

This wood species has been used for a variety of purposes so far, including furniture, flooring, and construction. Comprehending the properties of this wood species is critical to the determination of its suitability for various applications.

The wood is light and soft, with a pale yellowish color in the sapwood and yellowish and pale green in the heartwood. According to the research of Barboutis and Vassiliou [50], who studied the physical and mechanical properties of its wood, it was found to be of medium density, while demonstrating good mechanical properties that resemble those of several medium-density broadleaf species, such as white Ash and Chestnut. It was also observed that this wood species grown in Greece was superior in terms of modulus of rupture and resistance to compressive forces compared to the values reported in the literature [63]. It was concluded that due to its excellent appearance and unique design, it could be successfully used as sawn timber in many timber constructions and also as wood veneers [85,86].

Its wood can be easily dried, machined, glued, and finished with ease in forming attractive designs on both radial and tangential surfaces. Additionally, it is quite resistant to wear/aging, therefore, it can be used extensively in furniture construction [50].

Its wood is frequently reported to be uneven and subject to staining. It is suitable for construction, packaging, furniture-making material, pulp production. *A. altissima* can be utilized in the production of paper, whose properties could be comparable to those of *Eucalyptus globulus*, one of the most common species used for paper production, especially in temperate climate regions [87]. There is an urgent need to find sources of alternative fibers due to the increasing demand for paper, which is about to reach 521 million t/year [87]. Due to its rapid growth and tolerance to poor soils, drying, and pollution, the utilization of this species in paper production would help recover degraded environments and, in parallel, could contribute to the conservation of native forests.

According to research by Vasileiou et al. [85], except for swelling after 24 h of water immersion, tree-of-heaven plywood of 3-mm thickness showed proportionately superior qualities and mechanical strength to the poplar plywood of 3-mm thickness, respectively. Furthermore, in *Ailanthus* veneers, no knots were observed, while their pattern was considered much more attractive. Divya et al. [88] evaluated the potential use of *Ailanthus excelsa* as an alternative tree species for plywood production raw material. Wood demonstrated similar properties to other commercially important plywood species, indicating its potential as an alternative source for plywood production. However, limitations were highlighted in terms of sample size and lack of evaluation of other crucial properties of plywood.

Additionally, tree-of-heaven wood can be used in the fiber industry, in the production of particleboards and fiberboards [63]. Moreover, Li et al. [89] investigated the potential of *A. altissima* to be used in the production of particleboard. They found that the particles present similar physical and mechanical properties as particles from other hardwoods commonly used in particleboard production. However, they noted that the species' high extractive content could potentially adversely affect the adhesion properties of the particleboard.

Medved et al. [67] investigated the use of non-native wood species (black locust, silver fir, tree-of-heaven) in wood-plastic composites (WPCs) and examined their mechanical and physical properties. They concluded that tree-of-heaven could participate in the feedstock materials of WPCs since it combines high growth rates with satisfying wood fibers' hygroscopic and mechanical properties. Evaluating the potential use of the various products and wood of the studied species is necessary to reduce the costs of extensive tree clearance [90] in a way that this removal would be economically viable [91].

Tree-of-heaven could benefit from a mild or medium intensity heat treatment process in order to be modified to an aesthetically pleasing wood with enhanced hygroscopic nature and properties, facilitating its use in cabinetry and in variable indoor and outdoor non-structural applications [61]. A recent study by Bardak et al. [44] evaluated the chemical properties of *A. altissima* wood treated with a combination of tannin and oil-based resins. The results showed that the dimensional stability and resistance to fungal decay were improved, as well as its mechanical properties.

Olek et al. [92] revealed that heat treatment caused a decrease in hemicelluloses content and an increase in cellulose crystallinity and lignin content. The study also noted that heat treatment improved its dimensional stability and decay resistance. Barboutis and Kamperidou [61] also reported that thermal treatment affected the dimensional stability and water-absorbing capacity of wood in a positive way, decreasing equilibrium moisture content, swelling (tangential–radial), and adsorption percent, compared to untreated wood. The anisotropy of wood was decreased only to a small extent, while the wood color changed towards darker tones. Only the most intensive treatment negatively influenced the modulus of rupture and impact bending strength of wood, while the elasticity and compression strength of treated wood were proved to be similar to those of untreated wood, while the described changes were attributed to permanent changes of chemical constituents associated to thermal degradation during treatment.

Qian et al. [93] investigated the application of ultrasonic-assisted treatments to affect the properties of *A. altissima* wood. The wood was subjected to ultrasound at 320 W and 25 kHz while being combined with various alkali solutions (1%, 4%, and 8% NaOH), and the resulting changes in wood density and pore structure were analyzed. The ultrasonic-assisted treatment resulted in the breakdown or conversion of cell-wall components, mainly hemicelluloses, resulting in changes in the density and pore structure of the wood. In comparison to water immersion samples, ultrasonic-assisted samples produced a consistent self-shrinking wood block with higher oven-dried and bulk density and reduced porosity, particularly applying 1% and 4% NaOH. In alkali-treated samples, the distribution of pores moved towards smaller sizes, notably in ultrasonic-assisted samples. The researchers also discovered that ultrasonic-assisted treatment enhanced the relative content of macropores (>0.5 m), with samples treated with ultrasonic-1% NaOH reaching 86.10%. Ultrasonic-assisted treatments can be utilized to build a self-sustaining substrate with changing densities, pore architectures, and characteristics. The materials produced presented a high density, tiny pores, and excellent drainage. These findings provide important information on how to enhance the quality and possible applications of *A. altissima* wood.

2.8. Utilization in Paper, Pulp- and Nanocellulose-Based Products

A. altissima wood, bark, and leaves have been used for papermaking in different parts of the world, especially in China. The bark of the tree contains long and strong fibers that are suitable for producing strong paper, while the leaves contain short fibers that can be used to produce softer and smoother paper [94]. The bark fibers can be obtained by scraping the external bark of the tree, boiling it, and then introducing it into the pulp, mixed with water, and formed into sheets, which are dried and finished into paper. *A. altissima* paper has a distinctive light brown color and a slightly rough texture. The paper is also known for its strength and durability, making it suitable for various applications, such as bookbinding and printing [94].

There is limited literature concerning the utilization of this species in paper and pulp production, although there are some studies conducted evaluating the potential of this species for use in the paper industry. Nevertheless, *A. altissima* has been found to have a high cellulose content, which is a key component in the production of paper and pulp [31]. Tang et al. [95] investigated the suitability of *A. altissima* as a raw material for kraft pulp production and found that this species presented a similar pulp yield and kappa number (a measure of pulp quality), as other hardwood species commonly used in the paper industry. Baptista et al. [87] examined the potential of using this species as an alternative fiber source for papermaking in terms of the physical and mechanical properties of the produced paper, as well as the chemical composition of the fibers. The paper made of this species' fibers demonstrated satisfying mechanical properties, including high tensile strength and burst resistance, attributed mainly to the high cellulose content and low lignin content, which are desirable properties for papermaking. It was noticed that *A. altissima* had a lower lignin content than other hardwood species, which could potentially make it easier to bleach the pulp to achieve the desired whiteness [95]. Terzopoulou and Kamperidou [32], who examined the impact of tree age on the wood and bark properties, reported that as the tree age increases, the wood and bark present lower lignin content, though a linear increase in holocellulose and extractives. It was found that the optimum harvesting time for the highest possible utilization of holocellulose (as well as extractives) is after the 21st year when the cellulose, hemicelluloses, and extractives content increase. Further research is undoubtedly necessary to explore the environmental implications of using this tree species as a fiber source, as well as to develop more sustainable methods of fiber harvesting. Overall, although there is some evidence to suggest that *A. altissima* could be used as a raw material in the paper and pulp industry, further research is needed to fully understand the potential of the species for this application.

Almeida et al. [96] produced nanocellulose using invasive tree species of *A. altissima* and *Acacia dealbata*, in order to create high-value-added materials. The process involved producing bleached pulps from the wood of these trees using kraft cooking, followed by pre-treatment through either TEMPO-mediated oxidation (*A. dealbata*) or enzymatic hydrolysis (*A. altissima*) and high-pressure homogenization. The resulting hydrogels were characterized in terms of physical and chemical properties, including rheology and surface energy. The study found that nano/microfibrils could be obtained from the wood of these invasive species and that TEMPO cellulose nanofibrils formed strong gels with high-yield stress points and viscosities (tensile strength of 79 MPa, Young's modulus of 7.9 GPa, and transparency of 88%, although the water vapor barrier was modest). Films produced from cellulose hydrogels were found to be characterized by good mechanical and optical properties.

2.9. Utilization in Bioenergy Production

There has been an increasing interest in the potential use of *A. altissima* as a biomass feedstock for energy production. The fact that this species is characterized by a high growth rate and can grow in a great range of conditions makes it a potentially valuable feedstock for the production of biofuels or other bio-based products.

A. altissima wood indeed seems appropriate to be used in the production of high-quality firewood, compared to that of white oak, walnut, and birch species. This quality, of course, refers to older trees since the wood of younger trees that has been grown quickly is less energetically dense and more brittle, can be easily split, while it may present slightly higher ash contents. It generally acquires a high calorific value (18,040.17 $J \cdot g^{-1}$) and relatively low ash levels [66]. Kamperidou and Barboutis [66] concluded that *A. altissima* wood and bark marked high heating values and low ash content compared to *Robinia pseudoacacia* and other species, making those materials to be considered suitable for pellets production. Specifically, this wood species was found to contain 0.5–0.69% ash, which means that it can be used as a raw material for the production of pellets intended to be used for residential applications. The wood can be classified in the best quality class of pellets (ENplus-A1) and meets the requirements of EN14961-2 for very low ash values (<0.7%) [66]. *A. altissima* wood and bark pellets showed comparable physical and mechanical properties to pellets made from other commonly used wood species, indicating their potential for use as a feedstock in pellets production. Bučar et al. [97] also reported high potential of using *A. altissima* and *R. pseudoacacia*, as feedstock for pellet production, due to high energy density and low ash contents. It was noted that the use of invasive species as feedstock can provide a solution to the problem of invasive species management, as well as contribute to the development of sustainable energy systems.

It has also been used for coal production in many countries. Yang et al. [98] investigated the potential of *A. altissima* for use in co-firing with coal in power plants and found that it had similar combustion characteristics to other biomass feedstocks and could potentially be used as a renewable energy source in co-firing applications.

Jabeen et al. [27] focused on the production of biodiesel from *A. altissima* (Mill.) seed oil using a green and recyclable potassium hydroxide activated *A. altissima* cake and cadmium sulfide catalyst. The authors reported that the use of this species seed oil as a feedstock for biodiesel production is advantageous due to its non-edible nature and availability. It was mentioned that the use of green and recyclable potassium hydroxide-activated *Ailanthus* cake and cadmium sulfide catalyst is eco-friendly and sustainable. The optimal conditions for biodiesel production were found to be a molar ratio of 1:9 for oil to methanol, a catalyst loading of 1.0 wt.% based on oil weight, a reaction temperature of 60 °C, and a reaction time of 2 h. The produced biodiesel met the international standard specifications for biodiesel. A promising approach for the sustainable production of biodiesel using *A. altissima* (Mill.) seed oil and a green and recyclable potassium hydroxide activated *Ailanthus* cake and cadmium sulfide catalyst was presented, though it is crucial to note that cadmium sulfide is a toxic material, and its use should be carefully monitored to prevent any negative environmental impacts.

Additionally, the impact of graphene oxide nanoparticles, a novel fuel additive, on the engine performance and emission characteristics of a diesel engine was studied by Hoseini et al. [99]. Their results demonstrated that environmentally beneficial fuels may be produced using diesel fuel, graphene oxide (GO) nanoparticle additives, and *A. altissima* biodiesel.

Sahay and Rana [100] investigated the potential of hemicelluloses hydrolysate from *Ailanthus excelsa* wood as a feedstock for ethanol production, evaluating the chemical composition of the hydrolysate and its suitability for ethanol fermentation. They found that the hemicelluloses hydrolysate had a high sugar content and was potentially fermentable to ethanol. It had a low inhibitory effect on yeast growth, indicating its potential as a feedstock for ethanol production. Overall, the study highlighted the potential of *A. excelsa* wood as a feedstock for ethanol production and provided useful information for researchers and engineers interested in developing sustainable biofuels. However, further research is needed to explore the long-term sustainability and commercial viability of this process.

The study of Li and Chen [101] investigated the potential of *A. altissima* as a feedstock for the pyrolysis process and found that it had a high yield of bio-oil and a low ash content, which constitute desirable properties for a biofuel feedstock. However, the study indicated that this species presented a slightly lower calorific value compared to other biomass feedstocks, which could affect its economic viability. Ighalo and Adeniyi [102] investigated the in silico temperature sensitivity of the pyrolysis of tree-of-heaven, beech, and spruce, using the ASPEN Plus v8.8 software and simulated the pyrolysis process at temperatures ranging from 300 to 1000 °C, and analyzed the yields and properties of the pyrolysis products, including bio-oil, char, and gas. They found that the yield of bio-oil decreased with increasing temperature for all three species, with *Ailanthus* showing the highest bio-oil yield at all temperatures. The char yield was found to be increased with increasing temperature, while the gas yield decreased. The properties of the bio-oil produced varied with temperature and species, with *Ailanthus* showing the highest calorific value and the lowest acidity.

Liu et al. [103] investigated the potential of *A. altissima* for use in anaerobic digestion, a process that converts biomass into biogas, which can be used to generate electricity or heat, and reported that this species' biomass presented a high potential for methane production and could potentially be used as a feedstock for anaerobic digestion.

Generally, although there is significant evidence to suggest *A. altissima* to be used as a feedstock in energy production, further research is necessary to fully understand the potential of this species for such applications. In addition, it is important to consider the potential environmental impacts of using an invasive species in this way and to ensure that any use of *A. altissima* is in line with sustainable biomass production practices.

2.10. Challenges and Limitations of Ailanthus Utilization

Invasive alien species pose a significant threat to biodiversity conservation since they may disrupt ecosystem services, with subsequent socioeconomic and ecological implications that, in turn, affect human well-being. Global changes, such as rising temperature and anthropogenic disturbances, create favorable conditions for the introduction and expansion of invasive species, necessitating the proper management of this expansion and its impacts. Perez et al. [104] evaluated the potential impacts of four invasive alien species (*Ailanthus altissima*, *Baccharis halimifolia*, *Impatiens glandulifera*, and *Pueraria montana*) on three ecosystem services in Europe: Food provisioning, soil erosion regulation, and maintenance of biological diversity. Wild species diversity, erosion regulation, food provisioning (crops and livestock), harvested wild goods, and tourism or recreation were found to be adversely affected, according to the risk analysis protocol applied. Species distribution models indicated a shift in distribution ranges towards the north and east of Europe for these invasive species. Bivariate analysis revealed that the invasive species *I. glandulifera* and *A. altissima* were identified to have the highest potential impact on the contribution of natural ecosystems to crop provision and on soil erosion control, with specific mechanisms of impact, such as altering soil nutrient cycling, affecting soil microorganisms, or producing allelopathic compounds. According to the models, Western Europe and the British Isles were identified as the most affected regions, while the Mediterranean region showed lower projected impacts due to the northwards expansion of invasive species [104].

Because of its invasive nature, the constraints and limitations of *Ailanthus* use are triggered by a variety of socioeconomic concerns and ethical implications. To guarantee appropriate administration and usage, the following criteria must be carefully considered. First of all, the invasive habit of *Ailanthus* can have a severe impact on native ecosystems by outcompeting native vegetation, affecting soil chemistry, and disturbing normal ecological processes. To prevent aggravating ecological imbalances, utilization initiatives must properly examine and manage these repercussions. Secondly, the quick growth and abundant seed production of *Ailanthus* can result in the displacement of native vegetation species, and therefore, in a decrease in biodiversity and local food chain changes. This change of location has the potential to have a domino impact on ecosystem health and stability. Cross-breed between *Ailanthus* and native species can result in hybridization, which may cause genetic pollution and put at risk the inherited characteristics of local plant populations. This has the potential to have long-term implications for ecosystem dynamics and evolutionary processes [18]. Furthermore, harvesting *Ailanthus* for use may accidentally contribute to its spread since seeds can be dispersed during shipping and processing. This would raise the prospect of inadvertent introductions into new domains.

Its root system can cause damage to pavements, archaeological monuments, walls, and other structures because it causes erosion of substrates, and this presents one of its most important problems. Its effect can be chemical due to the secretion of organic acids from the roots decomposing calcium bicarbonate, which is the main component of the limestone used as a building material, or it can be mechanical, by the increase of the pressure of the roots, either above or near the buildings [105].

Positive impact has also been detected, as analyzed in this review article, which should be considered for inclusion in management cost-benefit evaluations. *A. altissima* stands out as a species that may provide wood of good quality and satisfying properties in accordance to its density and weight, medicinal ingredients, chemical products, biofuels, and has significant decorative appearance both as a standing tree and wood material produced [106]. The evaluation of beneficial effects should not be interpreted as an effort to counterbalance the negative effects but rather as a chance to contribute new information to scientists, managers, and policy-makers for the potential utilization of this species' biomass [107].

The possible influence of *Ailanthus* use in local economies and industries should be further and thoroughly studied. Depending on the extent of use, there may be resource competition between *Ailanthus*-based products and those derived from native/non-invasive plants. The decision to encourage Ailanthus use should be balanced against ethical concerns, such as the possible risk to natural ecosystems and traditional landscapes associated with our culture. It would be definitely critical to balance commercial interests with environmental and cultural values. Promoting the use of *Ailanthus* may unintentionally reinforce its existence and spread, complicating invasive species control efforts. Therefore, it is necessary to carefully examine if usage attempts may accidentally aid in its spread.

The need for management and mitigation strategies to address the potential impacts of invasive species on various ecosystem services seems to be of high urgency, especially in light of climate change and its interactions with invasive species spread.

In order to mitigate the potentially harmful impact, selective cultivation application would reduce the danger of biodiversity loss and genetic contamination, as well as the prioritization of the non-invasive, native, or less aggressive plant species cultivation. Rigorous measures implementation for *Ailanthus* production and trading would encourage the use of native species instead. Moreover, regular monitoring of *Ailanthus* and other alien species populations for evidence of hybridization and genetic contamination is of great importance, as well as the support of habitat restoration programs aimed at re-establishing native vegetation communities and increasing biodiversity in places impacted by Ailanthus invasion [104].

Since this species presents a preference for contaminated and disturbed soils and degraded habitats (along the roads on the outskirts and forest clearances, urban areas, and coastal zones of the Mediterranean islands [12,66,90]), it would be a good option to intensify our efforts towards the maintenance of good health of forest ecosystems, primarily avoiding severe degradation and applying rational and sustainable management.

3. Conclusions—Recommendation towards Future Research

Considering that *A. altissima* can be used for animal feed, bioenergy/biofuels, lumber, and wood-based products (plywood, particleboards, etc.) and composites, chemical industry products, pharmaceutical purposes, etc., it is frequently referred to as a species of several uses. When compared to other hardwood species of equivalent density and weight, its properties can be considered desirable, while it combines the advantages of pleasing appearance, high availability, fast growth, and low cost. It has been demonstrated that it is not appropriate for use in heavy structural applications, though it is acceptable for many other lighter applications, including furniture, boat construction, lining, decoration, pallets, matches, wood pulp, firewood, charcoal, etc., and its suitability for specialized applications of high added value is constantly being investigated. Despite the extensive research on the species of *A. altissima*, there are still several gaps in our knowledge about this invasive species. Here are a few areas where further research is needed.

There is a lack of genetic studies on *A. altissima* populations across its range. Understanding the genetic diversity and structure of these populations could provide insights into the species' evolutionary history and inform management strategies. There is limited research on the allelopathic effects of other plant species. Investigating the allelopathic compounds produced by this species could provide important information on its impact on plant communities and potential management options. Furthermore, there is limited research on the potential impacts of climate change on the distribution and spread of *A. altissima*. Taking into consideration the predicted changes in temperature and precipitation scenarios, it is important to understand how this invasive species may respond and adapt to these changes. There is also a lack of long-term studies on the effects of different management strategies for controlling *A. altissima*. Understanding the long-term ecological and economic impacts of different management approaches could help assist decision-making. There is limited research on the social and cultural impacts of *A. altissima* in areas where it is considered a valued or culturally significant species. This could include studies on the attitudes and perceptions of local communities towards the species and the impacts of its management on cultural practices and traditions. Although several studies have already been conducted in the field of potential application of this species in bio-based products and biofuels, they have been rather segmented, making it difficult to draw sound conclusions as regards the proper utilization of this species. Therefore, it would be of high importance to continue further examination of this species' biomass properties towards its rational utilization in an attempt to totally or partly substitute the respective conventional materials and products that are usually characterized by a high environmental impact, though without posing threats to the native ecosystem biodiversity.

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References

1. Ashori, A. Pulp and paper from kenaf bast fibers. *Fibers Polym. J.* **2006**, *7*, 26–29. [CrossRef]
2. Amoah, A.; Korle, K. Forest depletion in Ghana: The empirical evidence and associated driver intensities. *For. Econ. Rev.* **2020**, *2*, 61–80. [CrossRef]
3. Hickler, T.; Vohland, K.; Feehan, J.; Miller, P.A.; Smith, B.; Costa, L.; Giesecke, T.; Fronzek, S.; Carter, T.R.; Cramer, W.; et al. Projecting the Future Distribution of European Potential Natural Vegetation Zones with a Generalized, Tree Species-Based Dynamic Vegetation Model: Future Changes in European Vegetation Zones. *Glob. Ecol. Biogeogr.* **2012**, *21*, 50–63. [CrossRef]
4. Ruiz-Labourdette, D.; Schmitz, M.F.; Pineda, F.D. Changes in Tree Species Composition in Mediterranean Mountains under Climate Change: Indicators for Conservation Planning. *Ecol. Indic.* **2013**, *24*, 310–323. [CrossRef]
5. Santini, M.; Collalti, A.; Valentini, R. Climate Change Impacts on Vegetation Andwater Cycle in the Euro-Mediterranean Region, Studied by a Likelihood approach. *Reg. Environ. Chang.* **2014**, *14*, 1405–1418. [CrossRef]
6. Fyllas, N.M.; Koufaki, T.; Sazeides, C.I.; Spyroglou, G.; Theodorou, K. Potential Impacts of Climate Change on the Habitat Suitability of the Dominant Tree Species in Greece. *Plants* **2022**, *11*, 1616. [CrossRef]
7. Ashori, A. Non-wood fibers—A potential source of raw material in papermaking. *Polym-Plast Technol. Eng.* **2006**, *45*, 1133–1136. [CrossRef]
8. Giannotas, G.; Kamperidou, V.; Barboutis, I. Tree bark utilization in insulating bio-aggregates: A review. *Biofuels Bioprod. Biorefining* **2021**, *15*, 1989–1999. [CrossRef]

9. Copur, Y.; Guler, C.; Akgul, M.; Tascıoglu, C. Chemical properties of hazelnut husk and its suitability for particleboard production. *Build Environ.* **2007**, *42*, 2568–2572. [CrossRef]
10. Stefanidou, M.; Kamperidou, V.; Konstantinidis, A.; Koltsou, P.; Papadopoulos, S. Use of Posidonia oceanica fibres in lime mortars. *Constr. Build. Mater.* **2021**, *298*, 123881. [CrossRef]
11. Hytönen, J.; Nurmi, J. Heating value and ash content of intensively managed stands. *Wood Res.* **2015**, *60*, 71–82.
12. Kowarik, I.; Saumel, I. Biological flora of Central Europe: *Ailanthus altissima* (Mill.) Swingle. *Perspect. Plant Ecol. Evol. Syst.* **2007**, *8*, 207–237. [CrossRef]
13. Chen, S. *China Flora*; Science Press: Beijing, China, 1997; Volume 43, pp. 1–6.
14. Fu, L.; Hong, T. *Higher Plants of China; Beijing*; Book Gallery // Mike Riley: Phoenix, AZ, USA, 2000; Volume 13.
15. Saina, J.K.; Li, Z.; Gichira, A.W.; Liao, W. The Complete Chloroplast Genome Sequence of Tree of Heaven (*Ailanthus altissima* (Mill.) (Sapindales: Simaroubaceae), an Important Pantropical Tree. *Int. J. Mol. Sci.* **2018**, *19*, 929. [CrossRef] [PubMed]
16. Bailly, C. Anticancer properties and mechanism of action of the quassinoid ailanthone. *Phytother. Res.* **2020**, *34*, 2203–2213. [CrossRef]
17. Wang, Z.; He, Z.; Zhao, Z.; Yi, S.; Mu, J. Influence of ultrasound-assisted extraction on the pyrolysis characteristics and kinetic parameters of eucalyptus. *Ultrason. Sonochemistry* **2017**, *37*, 47–55. [CrossRef]
18. Espenschied-Reilly, A.L.; Runkle, J.R. Distribution and changes in abundance of *Ailanthus altissima* (Miller) Swingle in a southwest Ohio woodlot. *Ohio J. Sci.* **2008**, *108*, 16–22. Available online: https://kb.osu.edu/bitstream/handle/1811/48375/V108N2_16.pdf?sequence=1 (accessed on 1 June 2023).
19. Hu, S.Y. Ailanthus. *Arnoldia* **1979**, *39*, 29–50.
20. Brusa, A.; Holzapfel, C. Population structure of *Ailanthus altissima* (Simaroubaceae): The role of land-use history and management1. *J. Torrey Bot. Soc.* **2018**, *145*, 55–68. [CrossRef]
21. Miller, J. *Ailanthus altissima* (Mill.) Swingle ailanthus. In *Silvics of North America: Hardwoods*; Agriculture Handbook 654; Burns, R.M., Honkala, B.H., tech. coords, Eds.; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 1990; Volume 2, pp. 101–104.
22. Evans, C.W.; Moorhead, D.J.; Bargeron, C.T.; Douce, G.K. *Invasive Plant Responses to Silvicultural Practices in the South*; Bugwood Network BW-2006-03; The University of Georgia Bugwood Network: Tifton, GA, USA, 2006; 52p. Available online: http://www.invasive.org/silvicsforinvasives.pdf (accessed on 15 May 2023).
23. Pisuttu, C.; Piccolo, E.L.; Paoli, L.; Cotrozzi, L.; Nali, C.; Pellegrini, E.; Lorenzini, G. Physiochemical responses of *Ailanthus altissima* under the challenge of *Verticillium dahliae*: Elucidating the decline of one of the world's worst invasive alien plant species. *Biol. Invasions* **2023**, *25*, 61–78. [CrossRef]
24. Nunes, L.J.R. Creation of Value Chains for the Sustainability of Control and Eradication Actions on *Ailanthus altissima* (Mill.) Swingle. *Environments* **2022**, *9*, 64. [CrossRef]
25. Brihaspati, S.; Srivastava, A.K.; Prakash, O. A Comprehensive Review on Rare Biodiesel Feedstock Availability, Fatty Acid Composition, Physical Properties, Production, Engine Performance and Emission. *Process Integr. Optim. Sustain.* **2023**, 1–36. [CrossRef]
26. Pal, V.; Sharma, V.; Gour, V.S. *Ailanthus excelsa* Roxb. in India: A multipurpose "tree of Heaven" for semi-arid regions. *For. Trees Livelihoods* **2023**, 1–16. [CrossRef]
27. Jabeen, M.; Munir, M.; Abbas, M.M.; Ahmad, M.; Waseem, A.; Saeed, M.; Kalam, M.A.; Zafar, M.; Sultana, S.; Mohamed, A.; et al. Sustainable Production of Biodiesel from Novel and Non-Edible *Ailanthus altissima* (Mill.) Seed Oil from Green and Recyclable Potassium Hydroxide Activated *Ailanthus* Cake and Cadmium Sulfide Catalyst. *Sustainability* **2022**, *14*, 10962. [CrossRef]
28. Musa Tibin, M.A.; Alsharifm, Z.A.; Mohammed, A.Y.I.; Jadalla, J.B.; Ebrahiem, M.A. Effects of feeding *Ailanthus excelsa* (Roxb.) leaves on desert lamb's feed intake, nutrients digestibility and growth performance. *Int. J. Vet. Sci. Res.* **2021**, *7*, 113–117. [CrossRef]
29. Jat, H.S.; Singh, R.K.; Mann, J.S. Ardu (*Ailanthus* sp.) in arid ecosystem: A compatiblespecies for combating with drought and securing livelihood security of resource poor people. *Indian J. Tradit. Knowl.* **2011**, *10*, 102–113.
30. Ganai, A.; Ahmad, S.B.; Bhat, J.I.A. Utilization of Ailanthus (*Ailanthus altissima*) Leaves in Sheep Feeding. 2010. Available online: https://www.researchgate.net/publication/314083647_Utilization_of_ailanthus_Ailanthus_altissima_leaves_in_sheep_feeding (accessed on 31 July 2023).
31. Heisey, R.M. Allelopathy and the secret life of *Ailanthus altissima*. *Arnoldia* **1997**, *57*, 28–36.
32. Terzopoulou, P.; Kamperidou, V. Chemical characterization of Wood and Bark biomass of the invasive species of Tree-of-heaven (*Ailanthus altissima* (Mill.) Swingle), focusing on its chemical composition horizontal variability assessment. *Wood Mater. Sci. Eng.* **2021**, *17*, 469–477. [CrossRef]
33. Kalaskar, M.G.; Sapkal, P.R.; Tatiya, A.U.; Jain, P.D.; Surana, S.J. Morphoanatomical and physicochemical studies on *Ailanthus excelsa* roxb. stem bark: A tree of heaven. *J. Drug Deliv. Ther.* **2019**, *9*, 128–131. [CrossRef]

34. Luís, Â.; Gil, N.; Amaral, M.E.; Domingues, F.; Duarte, A.P. *Ailanthus altissima* (Miller) Swingle: A source of bioactive compounds with antioxidant activity. *BioResources* **2012**, *7*, 2105–2120. Available online: https://bioresources.cnr.ncsu.edu/wp-content/uploads/2016/06/BioRes_07_2_2105_Luis_GADD_Ailanthus_Bioactiv_Cpds_Antioxidant_Activity_2555.pdf (accessed on 15 July 2023). [CrossRef]
35. Caramelo, D.; Pedro, S.I.; Marques, H.; Simão, A.Y.; Rosado, T.; Barroca, C.; Gominho, J.; Anjos, O.; Gallardo, E. Insights into the Bioactivities and Chemical Analysis of *Ailanthus altissima* (Mill.) Swingle. *Appl. Sci.* **2021**, *11*, 11331. [CrossRef]
36. Chuang, L.; Liu, S.; Biedermann, D.; Franke, J. Identification of early quassinoid biosynthesis in the invasive tree of heaven (*Ailanthus altissima*) confirms evolutionary origin from protolimonoids. *Front. Plant Sci.* **2022**, *13*, 958138. [CrossRef]
37. Pettersen, R.C. The chemical composition of wood. In *The Chemistry of Solid Wood*; Rowell, R.M., Ed.; Advances in Chemistry Series, 207; American Chemical Society: Washington, DC, USA, 1984; pp. 57–126.
38. Demirbas, A. Biodiesel from Wood Oils in Compressed Methanol. *Energy Sources Part A: Recovery Util. Environ. Eff.* **2009**, *31*, 1530–1536. [CrossRef]
39. Samariha, A.; Kiaei, M. Chemical Composition Properties of Stem and Branch in *Alianthus altissima* Wood. *Middle-East J. Sci. Res.* **2011**, *8*, 967–970.
40. Hosseinzade, A.; Arabtabar, H.; Golbabaei, F.; Familian, H.; Sadraei, N.; Habibi, M. Wood Properties of Eucalyptus steriaticalyx grown in southern region of Iran. *Res. Inst. For. Rangel.* **2001**, *243*, 62–123.
41. Talaeipour, M.; Hemmasi, A.H.; Ebrahimpour Kasmani, J.; Mirshokraie, A.; Khademieslam, H. Effects of fungal treatment on structural and chemical features of Hornbeam chips. *BioResources* **2010**, *5*, 477–487. [CrossRef]
42. Saidur, R.E.; Abdelaziza, A.; Demirbas, A.; Hossain, M.S.; Mekhilef, S. A review on biomass as a fuel for boiler. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2262–2289. [CrossRef]
43. Rahman, H.M.A.; Javaid, S.; Ashraf, W.; Rasool, M.F.; Saleem, H.; Khan, S.A.; Ul-Haq, Z.; Anjum, S.M.; Ahmad, T.; Alqahtani, F. Effects of long-term *Ailanthus altissima* extract supplementation on fear, cognition and brain antioxidant levels. *Saudi Pharm. J.* **2023**, *31*, 191–206. [CrossRef]
44. Bardak, S.; Nemli, G.; Tiryaki, S. The Influence of Raw Material Growth Region, Anatomical Structure and Chemical Composition of Wood on the Quality Properties of Particleboards. *Maderas. Cienc. Tecnol.* **2017**, *19*, 363–372. [CrossRef]
45. Küçük, M.M.; Demirbaş, A. Kinetic study on hydrolysis of biomass (*Ailanthus altissima* chips) by using alkaline-glycerol solution. *Energy Convers. Manag.* **1999**, *40*, 1397–1403. [CrossRef]
46. Khattak, T.M.; Ghazi, J.Á.M.I.L.A. Suitability of some non-commercial fast growing wood yielding trees growing in Azad Kashmir for the production of pulp and paper. *Pak. J. Bot.* **2001**, *33*, 729–732.
47. Demirbas, M.F. Biorefineries for biofuel upgrading: A critical review. *Appl. Energy* **2009**, *86*, S151–S161. [CrossRef]
48. Wagenführ, R. *Holzatlas, Wood Atlas*, 6th ed.; Fachbuchverlag im Carl Hanser Verlag: Leipzig, Germany, 2007. (In German)
49. Hassan, K.; Tippner, J. Acoustic properties assessment of neem (*Azadirachta indica* A. Juss.) wood from trees irrigated with secondarily treated wastewater. *BioResources* **2019**, *14*, 2919–2930. Available online: https://bioresources.cnr.ncsu.edu/resources/acoustic-properties-assessment-of-neem-azadirachta-indica-a-juss-wood-from-trees-irrigated-with-secondarily-treated-wastewater/ (accessed on 10 January 2023). [CrossRef]
50. Barboutis, I.; Vassiliou, V. Physical and Mechanical Properties of the Wood of *Ailanthus altissima* (Miller) Swingle. In Proceedings of the 14th Pan-Hellenic Forestry Conference, Patra, Greece, 1–4 November 2009.
51. Arnaboldi, F.; Conedera, M.; Fonti, P. Caratteristiche anatomiche e auxometriche di Ailanthus altissima. Una specie arborea a carattere invasivo. *Sherwood* **2003**, *91*, 19–23. Available online: https://www.dora.lib4ri.ch/wsl/islandora/object/wsl:8663 (accessed on 31 July 2023).
52. Kúdela, J.; Mamoňová, M. Tree-of-heaven wood (*Ailanthus altissima*, Mill.)—Structure and properties. *Wood Struct. Prop.* **2006**, *6*, 275–287.
53. Balabán, K. *Nauka o Dřevě. 1. Část: Anatomie Dřeva*; Státní Zemědělské Nakladatelství: Praha, Czech Republic, 1955; 220p.
54. Demeter, A.; Saláta, D.; Tormáné Kovács, E.; Szirmai, O.; Trenyik, P.; Meinhardt, S.; Rusvai, K.; Verbényiné Neumann, K.; Schermann, B.; Szegleti, Z.; et al. Effects of the Invasive Tree Species Ailanthus altissima on the Floral Diversity and Soil Properties in the Pannonian Region. *Land* **2021**, *10*, 1155. [CrossRef]
55. Li, X.; Li, X.; Li, Y.; Li, C.; Li, J. Effect of moisture content on physical and mechanical properties of *Ailanthus altissima* wood. *BioResources* **2020**, *15*, 3142–3156.
56. Danihelová, A.; Čulík, M.; Danihelová, Z. Assessment of Properties of Ailanthus Wood for Xylophone Bars. *Akustika* **2015**, *24*, 42–49. Available online: https://www.akustikad.com/ (accessed on 31 July 2023).
57. Merhar, M.; Bučar, G.D.; Merela, M. Machinability Research of the Most Common Invasive Tree Species in Slovenia. *Forests* **2020**, *11*, 752. [CrossRef]
58. Özçifçi, A.; Hiziroglu, S. Physical and mechanical properties of *Ailanthus altissima* wood. *Eur. J. Wood Wood Prod.* **2013**, *71*, 179–181.
59. Li, X.; Li, Y.; Ma, S.; Zhao, Q.; Wu, J.; Duan, L.; Xie, Y.; Wang, S. Traditional uses, phytochemistry, and pharmacology of *Ailanthus altissima* (Mill.) Swingle bark: A comprehensive review. *J. Ethnopharmacol.* **2021**, *275*, 114121. [CrossRef]
60. Olsson, S.; Johansson, M.; Westin, M.; Ostmark, E. Reactive UV-absorber and epoxy functionalized soybean oil for enhanced UV-protection of clear coated wood. *Polym. Degrad. Stab.* **2014**, *110*, 405–414. [CrossRef]
61. Barboutis, I.; Kamperidou, V. Impact of Heat Treatment on the Quality of Tree-of-Heaven Wood. *Drv. Ind.* **2019**, *70*, 351–358. [CrossRef]

62. Požgaj, A.; Kurjatko, S.; Chovanec, D.; Babiak, M. *Štruktúra a Vlastnosti Dreva*, 2nd ed.; Príroda: Bratislava, Slovakia, 1997; 488p.
63. Moslemi, A.A.; Bhagwat, S.G. Physical and Mechanical Properties of the Tree of Heaven. *Wood Fiber* **1970**, *1*, 319–323.
64. Panayotov, P.; Kalmukov, K.; Panayotov, M. Biological and wood properties of *Ailanthus altissima* (mill.) swingle. *For. Ideas* **2011**, *17*, 122–130. Available online: https://forestry-ideas.info/files/issue/Forestry_Ideas_BG_2011_17_2_2.pdf (accessed on 5 May 2023).
65. Miao, X.; Chen, H.; Lang, Q.; Bi, Z.; Zheng, X.; Pu, J. Characterization of *Ailanthus altissima* Veneer Modified by Urea-formaldehyde Pre-polymer with Compression Drying. *BioResources* **2014**, *9*, 5928–5939. Available online: https://jtatm.textiles.ncsu.edu/index.php/BioRes/article/view/BioRes_09_4_5928_Miao_Ailanthus_altissima_Veneer (accessed on 1 January 2023). [CrossRef]
66. Barboutis, I.; Kamperidou, V. Utilization perspectives of wood and bark of the invasive species of *Ailanthus* and *Acacia* in the production of pellets. In Proceedings of the International Forestry and Environment Symposium, Trabzon, Turkey, 7–10 November 2017.
67. Medved, S.; Tomec, D.K.; Balzano, A.; Merela, M. Alien Wood Species as a Resource for Wood-Plastic Composites. *Appl. Sci.* **2021**, *11*, 44. [CrossRef]
68. Szabolcs, K.; Varga, D. Physical and mechanical properties of wood from invasive tree species. *Maderas Cienc. Tecnol.* **2021**, *23*, 1–8. [CrossRef]
69. Howard, J.L. Ailanthus altissima. In: Fire Effects Information System, [Online]. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). 2004. Available online: http://www.fs.fed.us/database/feis/S (accessed on 1 February 2023).
70. Kozuharova, E.; Lebanova, H.; Getov, I.; Benbassat, N.; Kochmarov, V. *Ailanthus altissima* (Mill.) Swingle a terrible invasive pest in Bulgaria or potential useful medicinal plant? Review paper. *Bothalia J.* **2014**, *44*, 213–230.
71. Cheng, J.Q.; Yang, J.J.; Liu, P. *Wood Science*; Chinese Forestry Publishing House: Beijing, China, 1992.
72. Zhu, T.H.; Zhang, W.N.; Gao, Y.Y.; Pei, Z.; Zhao, L.K.; Jiang, T.; Wu, Y.B.; Ni, Z.Y. Two New Tetracyclic Triterpenoids from the Fresh Bark of *Ailanthus altissima*. *Chem. Nat. Compd.* **2023**, *59*, 73–75. [CrossRef]
73. Gürbüz, R.; Kahramanoğlu, I. Possibility of using leaf extracts of tree-of-heaven (*Ailanthus altissima* (Mill.) Swingle) for the postharvest quality preservation of fresh apricot fruits. *Physiol. Mol. Plant Pathol.* **2021**, *113*, 101594. [CrossRef]
74. Kim, S.R.; Park, Y.; Li, M.; Kim, Y.K.; Lee, S.; Son, S.Y.; Lee, S.; Lee, J.S.; Lee, C.H.; Park, H.H.; et al. Anti-inflammatory effect of *Ailanthus altissima* (Mill.) Swingle leaves in lipopolysaccharide-stimulated astrocytes. *J. Ethnopharmacol.* **2022**, *286*, 114258. [CrossRef] [PubMed]
75. Andonova, T.; Muhovski, Y.; Slavov, I.; Vrancheva, R.; Georgiev, V.; Apostolova, E.; Naimov, S.; Mladenov, R.; Pavlov, A.; Dimitrova-Dyulgerova, I. Phenolic profile, antioxidant and DNA-protective capacity, and microscopic characters of *Ailanthus altissima* aerial substances. *Plants* **2023**, *12*, 920. [CrossRef] [PubMed]
76. Bajwa, R.; Farooq, M.; Cheema, Z.A.; Siddique, K.H.M. Allelopathic effects of *Ailanthus altissima* extracts on germination and growth of several crop and weed species. *Plant Growth Regul.* **2012**, *67*, 247–256.
77. Galatowitsch, S.M.; Anderson, N.O.; Ascher, P.D. Invasiveness in wetland plants in temperate North America. *Ecol. Eng.* **1999**, *13*, 145–167. [CrossRef]
78. Novak, M.; Novak, N.; Milinović, B. Differences in allelopathic effect of tree of heaven root extracts and isolated ailanthone on test-species. *J. Cent. Eur. Agric.* **2021**, *22*, 611–622. Available online: https://jcea.agr.hr/en/issues/article/3098 (accessed on 31 July 2023). [CrossRef]
79. Kozuharova, E.; Pasdaran, A.; Al Tawaha, A.R.; Todorova, T.; Naychov, Z.; Ionkova, I. Assessment of the Potential of the Invasive Arboreal Plant *Ailanthus altissima* (Simaroubaceae) as an Economically Prospective Source of Natural Pesticides. *Diversity* **2022**, *14*, 680. [CrossRef]
80. Hopson, C.A.; Natarajan, P.; Shinde, S.; Kshetry, A.O.; Challa, K.R.; Valenciana, A.P.; Nimmakayala, P.; Reddy, U.K. Physiological and Transcriptomic Analysis of *Arabidopsis thaliana* Responses to Ailanthone, a Potential Bio-Herbicide. *Int. J. Mol. Sci.* **2022**, *23*, 11854. [CrossRef]
81. Pavela, R.; Zabka, M.; Tylova, T.; Kresinova, Z. Insecticidal activity of compounds from *Ailanthus altissima* against spodoptera littoralis larvae. *Pak. J. Agric. Sci.* **2014**, *51*, 101–112. Available online: https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=45082669 (accessed on 31 July 2023).
82. Tanaskovic, S.T.; Gvozdenac, S.; Kolarov, R.; Prvulovic, D. Antifeeding and Insecticidal Activity of *Ailanthus altissima* and Morus alba Extracts Against Gipsy Moth (*Lymantria dispar* (L.), Lepidoptera, Lymantridae) Larvae Under Laboratory Conditions. *J. Entomol. Res. Soc.* **2021**, *23*, 197–212. [CrossRef]
83. Lee, K.; Han, B.; Cho, W. The appropriate mounding height and selection of ornamental trees on consideration of the environmental characteristics in an apartment complex. In the case of Sanggyoi-Dong sanitary landfill. *Korean J. Environ. Ecol.* **1997**, *11*, 137–148.
84. Mohebzadeh, F.; Motesharezadeh, B.; Jafari, M.; Zare, S.; Aman, M.S. Remediation of heavy metal polluted soil by utilizing organic amendments and two plant species (*Ailanthus altissima* and *Melia azedarach*). *Arab. J. Geosci.* **2021**, *14*, 1211. [CrossRef]
85. Vasileiou, V.; Barboutis, I.; Kamperidou, V. Properties of Thin 3-PLY Plywood Constructed With Tree-of-Heaven and Poplar Wood. In Proceedings of the International Conference "Wood Science and Engineering in the Third Millennium"—ICWSE 2011, Brasov, Romania, 3–5 November 2011; pp. 323–329. Available online: http://users.auth.gr/jbarb/Publications/VASILEIOU%20ICWSE%202011%20.pdf (accessed on 31 July 2023).

86. Barboutis, I.; Kamperidou, V. Properties of two different thicknesses 3-ply plywood of Tree-Of-Heaven veneers. In Proceedings of the 22nd International Scientific Conference "Wood is Good-EU Preaccession Challenges of the Sector", Zagreb, Croatia, 21 October 2011.
87. Baptista, P.; Costa, A.P.; Simoes, R.; Amaral, M.E. *Ailanthus altissima*: An alternative fiber source for papermaking. *Ind. Crops Prod.* **2014**, *52*, 32–37. [CrossRef]
88. Divya, M.P.; Parthiban, K.T.; Manivasakan, S.; Packialakshmi, M. *Ailanthus excelsa*: An alternate tree species for plywood production. *Pharma Innov. J.* **2022**, *SP-11*, 1184–1187.
89. Li, H.; Fang, G.; Cai, L.; Li, J. Utilization of *Ailanthus altissima* (Mill.) Swingle for particleboard production. *BioResources* **2018**, *13*, 1038–1050.
90. VDOF. *Control and Utilization of Tree of Heaven: A Guide for Virginia Landowners*; Virginia Department of Forestry: Charlottesville, VA, USA, 2009. Available online: https://www.dof.virginia.gov/trees/tree-of-heaven.htm (accessed on 1 June 2022).
91. Zhu, S.; Fang, X.; Wu, Q. Characterization of *Ailanthus altissima* Fiber as a Potential Reinforcement in Polymer Composites. *J. Nat. Fibers* **2017**, *14*, 462–474.
92. Olek, W.; Bonarski, J.T. Texture changes in ther-mally modified wood. *Arch. Metall. Mater.* **2008**, *53*, 207–211. Available online: http://journals.pan.pl/dlibra/jour-nal/97808 (accessed on 31 July 2023).
93. Qian, J.; Gao, J.; He, Z.; Yi, S. Self-shrinking *Ailanthus altissima* substrate obtained by ultrasonic-assisted treatment: Density and pore structure characteristics. *Ind. Crops Prod.* **2022**, *175*, 114221. [CrossRef]
94. Ferreira, P.J.; Gamelas, J.A.; Carvalho, M.G.; Duarte, G.V.; Canhoto, J.M.; Passas, R. Evaluation of the papermaking potential of *Ailanthus altissima*. *Ind. Crops Prod.* **2013**, *42*, 538–542. [CrossRef]
95. Tang, X.; Guo, J.; Yan, Z.; Wu, X.; Wang, S. Kraft pulp production from *Ailanthus altissima*. *J. Wood Sci.* **2015**, *61*, 501–507.
96. Almeida, R.O.; Ramos, A.; Alves, L.; Potsi, E.; Ferreira, P.J.T.; Carvalho, M.G.V.S.; Rasteiro, M.G.; Gamelas, J.A.F. Production of nanocellulose gels and films from invasive tree species. *Int. J. Biol. Macromol.* **2021**, *188*, 1003–1011. [CrossRef]
97. Bučar, G.D.; Gospodarič, B.; Smolnikar, P.; Stare, D.; Kranjc, N.; Prislan, P. Invasive Species as Raw Material for Pellets Production. In Proceedings of the 30th International Conference on Wood Science and Technology—ICWST 2019, Zagreb, Croatia, 12–13 December 2019; "Implementation of wood science in woodworking sector" & 70th Anniversary of Drvna Industrija Journal. pp. 60–68. Available online: https://www.sumfak.unizg.hr/site/assets/files/3845/proceedings_icwst-2019.pdf (accessed on 1 February 2022).
98. Yang, H.; Chen, Q.; Chen, H. Co-firing of *Ailanthus altissima* with coal in a circulating fluidized bed combustor. *Fuel Process. Technol.* **2015**, *131*, 387–393.
99. Hoseini, S.S.; Najafi, G.; Ghobadian, B.; Ebadi, M.T.; Mamat, R.; Yusaf, T. Novel environmentally friendly fuel: The effects of nanographene oxide additives on the performance and emission characteristics of diesel engines fuelled with *Ailanthus altissima* biodiesel. *Renew. Energy* **2018**, *125*, 283–294. [CrossRef]
100. Sahay, S.; Rana, R.S. Hemicellulose hydrolysate from *Ailanthus excelsa* wood potentially fermentable to ethanol. *J. Trop. For. Sci.* **2017**, *29*, 172–178.
101. Li, X.; Chen, Y. Pyrolysis of *Ailanthus altissima* for bio-oil production: Effect of pyrolysis conditions on product yields and characteristics. *Biomass Bioenergy* **2016**, *85*, 167–176.
102. Ighalo, J.O.; Adeniyi, A.G. An In Silico Temperature Sensitivity Study of the Pyrolysis of Beech, *Ailanthus* and *Spruce*. *Eur. J. Sustain. Dev. Res.* **2020**, *4*, em0137. [CrossRef] [PubMed]
103. Liu, Z.; Li, L.; Yuan, X. Anaerobic digestion of *Ailanthus altissima* for biogas production: Kinetics, methane yield, and energy balance. *Energy Sources Part A Recovery Util. Environ. Eff.* **2017**, *39*, 667–672.
104. Pérez, G.; Vilà, M.; Gallardo, B. Potential impact of four invasive alien plants on the provision of ecosystem services in Europe under present and future climatic scenarios. *Ecosyst. Serv.* **2022**, *56*, 101459. [CrossRef]
105. Almeida, M.T.; Mouga, T.; Barracosa, P. The weathering ability of higher plants. The case of *Ailanthus altissima* (Miller) Swingle. *Int. Biodeterior. Biodegrad.* **1994**, *33*, 333–343. [CrossRef]
106. Sladonja, B.; Susek, M.; Guillermic, J. Review on invasive tree of heaven (*Ailanthus altissima* (Mill.) Swingle) conflicting values: Assessment of its ecosystem services and potential biological threat. *Environ. Manag.* **2015**, *56*, 1009–1034. [CrossRef]
107. Vimercati, G.; Kumschick, S.; Probert, A.F.; Volery, L.; Bacher, S. The importance of assessing positive and beneficial impacts of alien species. *NeoBiota* **2020**, *62*, 525–545. [CrossRef]