

Paulownia biomass under drought and salinity: From stress adaptation to functional materials and biorefinery valorization

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ABSTRACT

As semi-arid and salt-affected landscapes expand under climate change and land degradation, interest has increased in fast-growing woody biomass that can support both land rehabilitation and material production. Paulownia species and commercial hybrids are frequently promoted for these purposes because of their rapid juvenile growth, coppicing capacity, and lignocellulosic composition. Reported performance, however, varies substantially across genotypes, sites, and management regimes. This review evaluates the biological basis, establishment requirements, drought and salinity responses, wood and fiber properties, functional-material applications, and integrated biorefinery pathways of *Paulownia* spp. Field observations, controlled stress experiments, wood-characterization results, and laboratory processing studies are interpreted separately through a genotype $\times$ environment $\times$ management (G $\times$ E $\times$ M) framework. The specific synthesis is a proposed evidence chain from site and genotype through feedstock properties to end use: field evidence can inform plantation feasibility, whereas processing results establish candidate applications but cannot establish the advantages of stress-grown biomass without paired feedstock measurements. Field studies support substantial variation in growth with water supply, drainage, soil condition, and genotype, but available studies do not establish a universal drought or salinity threshold or a consistently abrupt response. Selected hybrids perform well in particular managed trials; comparative superiority across environments and lower invasion risk remain unverified for many clones. Low wood density constrains some structural and volumetric fuel applications, while laboratory fractionation and biochar studies show process feasibility under specified conditions, not industrial superiority or a demonstrated benefit of stress-grown feedstock. Paulownia is thus a management-dependent candidate for site-matched biomass production. This review distinguishes comparatively supported site and material constraints from hypotheses about genotype-specific stress limits and integrated biorefinery value. Field validation, genetically identified planting material, measured soil and water conditions, feedstock characterization, and comparative process assessment are required before regional or industrial recommendations can be made.

Keywords: *Paulownia* spp.; lignocellulosic biomass; drought stress; salinity; wood materials; biochar; biorefinery; genotype–environment–management interaction.

INTRODUCTION

The modern world is currently facing a wide range of problems that adversely affect biocenoses. In particular, increasing aridity, the expansion of saline and drought-affected soils, land degradation, as well as adverse anthropogenic impacts, substantially affect modern agroforestry practices. Given that forestry is associated not only with the production of woody biomass but also with maintaining the ecological stability of different regions, there is growing interest in the planting and cultivation of fast-growing woody plants characterized by high biological productivity (Badalamenti et al., 2020; Facciotto et al., 2020).

The genus *Paulownia* (family *Paulowniaceae*) comprises approximately nine species and hundreds of clones and is considered one of the fastest-growing groups of woody plants in the world. China and East Asia are regarded as the native regions of this genus, where its species have been cultivated for more than two thousand years (Zhu et al., 1986; Drvodelić, 2018). Historically, *Paulownia* species have been used in traditional agroforestry systems and have been valued for their rapid growth during the early stages of vegetative development, their capacity for coppice regeneration, and their compatibility with crops growing in the lower forest strata. Since the seventeenth century, several species of the genus have been introduced into regions of Europe and North America, initially as ornamental plants and subsequently as promising species for plantation cultivation.

Paulownia wood, having low density and dimensional stability, in combination with its high growth rate and regenerative capacity after harvesting, makes it attractive from an industrial perspective and enables its use for various purposes (Bodnar et al., 2014; Bergmann, 1998; Silvestre et al., 2005). At the same time, the rapid development of the *Paulownia* root system improves soil structure and aeration, whereas its large leaf surface area and high assimilation capacity contribute to the uptake of carbon dioxide from the atmosphere (Tian et al., 2023; Salguero et al., 2016). All of the above-mentioned factors provide an understanding of the important role of cultivating this plant.

First and foremost, growing conditions play an important role in the cultivation of *Paulownia*. Unfavourable conditions, such as soil salinity, high clay content, water deficiency, and

mineral nutrient imbalance, can substantially restrict plant growth and deteriorate wood quality (Ayala-Astorga et al., 2009; García-Morote et al., 2014). Various studies in this field indicate that plant productivity declines sharply when certain threshold levels of water deficit and high salt concentrations in the soil are exceeded (Ayala-Astorga et al., 2009). This pattern indicates relatively narrow limits of the plant's ecological tolerance, despite its high growth rate during the early stages of post-embryonic development. In addition, reports of the invasive behavior of *Paulownia tomentosa* in some regions of North America emphasize the importance of species and hybrid selection, reproductive control, and monitoring strategies (Snow, 2015).

These examples highlight that *Paulownia* should not be regarded as a universal agricultural solution for marginal lands, but rather as a genus whose successful cultivation depends on the appropriate alignment of genotype, site conditions, and management practices. Considering this fact, there is a lack of review articles addressing the cultivation of *Paulownia* under extreme environmental conditions.

This review synthesizes *Paulownia* cultivation under semi-arid and salt-affected conditions alongside wood, fiber, biochar, and biorefinery studies. Its added inference is an evidence chain linking verified genotype, measured site stress, feedstock composition and physical properties, and product-specific processing, while identifying where the links have not been tested together. Field growth findings cannot establish process advantages, and laboratory conversion of unspecified or unstressed feedstock cannot establish the value of biomass from drought- or salt-affected sites. The resulting framework identifies measurements needed to test these hypotheses rather than claiming a universal optimum.

The G×E×M framework organizes a proposed causal sequence: genotype and site management shape field survival and growth; growth environment may alter biomass composition and physical properties; and measured feedstock properties influence product performance and processing. The first relationship has field evidence for particular sites, whereas the stress-to-feedstock-to-product pathway remains sparsely tested using paired measurements. Conceptual diagrams and qualitative rankings summarize this interpretation and do not identify statistical interactions, common thresholds, or effect sizes.

Figure 1 does not merely illustrate the conceptual structure of the Genotype $\times$ Environment $\times$ Management (G $\times$ E $\times$ M) framework, but highlights the dynamic balance required to sustain productive growth under stress conditions. The model indicates that plantation performance is not determined by any single factor, but emerges from the interaction between genetic potential, environmental constraints, and the intensity of silvicultural intervention (Jakubowski, 2022; Merriman et al., 2025). The figure proposes a distinction between survival and productive growth, but cannot demonstrate a critical transition or its location. Field irrigation studies, controlled salinity treatments, and laboratory analyses differ in genotype, duration, and exposure metric; the observed changes cannot be pooled to establish an abrupt general response (García-Morote et al., 2014; Ayala-Astorga et al., 2009).

This pattern explains why Paulownia plantations may exhibit high early growth but subsequently experience sudden stagnation under suboptimal conditions, particularly where irrigation and soil conditions are not adequately controlled (García-Morote et al., 2014; Merriman et al., 2025). Thus, Figure 1 supports the interpretation that Paulownia should be understood as a condition-sensitive system, where management acts as a control variable capable of temporarily compensating for environmental limitations, but not eliminating them (Zhu et al., 1986; Young & Lundgren, 2023).

BIOLOGICAL AND ECOLOGICAL BASIS OF PAULOWNIA

Taxonomic position, species diversity, and geographic distribution

The genus *Paulownia* is currently classified within the family *Paulowniaceae*, based on molecular phylogenetic and morphological analyses that led to its separation from the family *Scrophulariaceae* (Zhao et al., 2025; Young & Lundgren, 2023). The genus comprises approximately nine species of fast-growing deciduous woody plants, among which *P. tomentosa*, *P. elongata*, *P. fortunei*, *P. kawakamii*, *P. taiwaniana*, and *P. fargesii* are the most frequently studied. China is recognized as both the center of origin and the primary region of domestication of these species (Zhu et al., 1986; Xiong & Chen, 1992; Kumar et al., 2019). Although these species share several common morphological characteristics, such as large leaves, hollow stems, and rapid growth during juvenile stages, their growing conditions, reproductive strategies, and tolerance to abiotic stress differ substantially. Based on the different adaptive capacities of Paulownia species, efforts have been made for many years to develop cultivars, genotypes, and interspecific hybrids (Pożoga et al., 2019).

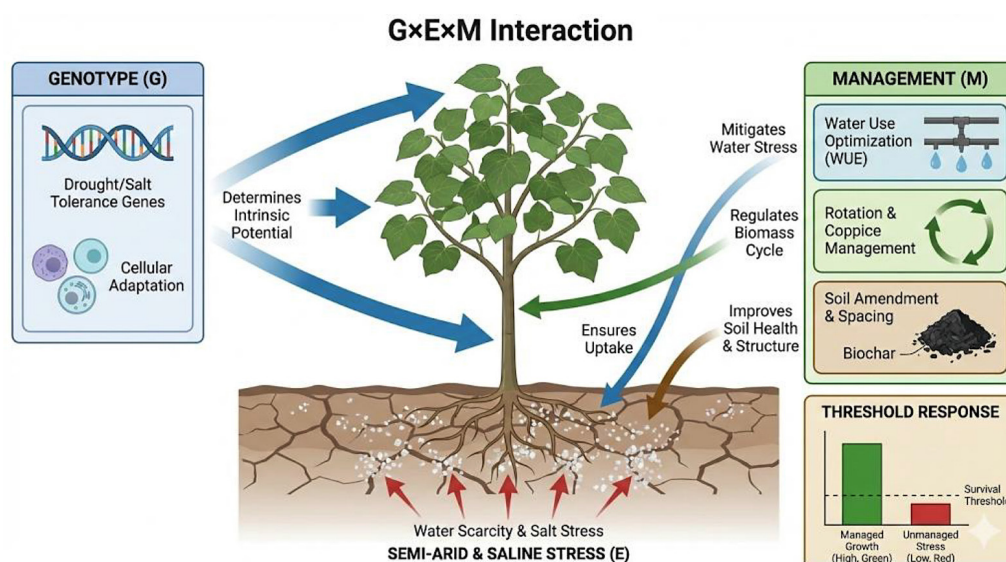


Figure 1. A conceptual diagram illustrating the genotype $\times$ environment $\times$ management (G $\times$ E $\times$ M) interaction framework applied to Paulownia plantations in semi-arid and saline regions. The model highlights how specific silvicultural interventions (management) can modulate genetic potential (genotype) to mitigate environmental stressors (environment), ultimately determining the threshold between plantation survival and productive growth.

Species-specific ecological traits and environmental constraints

Species belonging to the genus *Paulownia* share a number of distinct morphological characteristics, the most prominent of which include rapid growth during the early stages of development, a large leaf area, and a pronounced capacity for vegetative regeneration through coppicing. Despite these similarities at the morphological level, substantial differences in ecological behaviour become apparent upon closer examination of growth regulation, stress responses, reproductive strategies, and dependence on stand management practices. Each of the *Paulownia* species investigated is characterized by a specific combination of ecological and silvicultural traits that determines its suitability for particular environmental conditions and cultivation systems. Therefore, there are no universal conditions that can be considered equally suitable for all species.

These differences are particularly important outside the natural range of the genus, where *Paulownia* species are frequently cultivated under semi-arid climatic conditions or on soils affected by salinity and structural constraints. At the same time, the analysis of species and their growing conditions has revealed several common patterns. An apparent trade-off between broad adaptability and controllability is a working hypothesis rather than an established species ranking. Reproductive capacity and local recruitment must be checked

for each clone and receiving region; the absence of published naturalization records is not evidence of low invasive potential. The natural distribution of *Paulownia* in East Asia and its subsequent global introduction are presented in Figure 3. based on occurrence data obtained from the Global Biodiversity Information Facility (GBIF). These distribution patterns provide an important context for interpreting interspecific differences in productivity and ecological impacts (Young & Lundgren, 2023).

Figure 3 shows that, as a result of intentional introduction, *Paulownia* has spread far beyond its original ecological niche. However, establishment in regions differing in climatic and edaphic conditions results in substantial variability in growth performance and ecological responses (Essl et al., 2007; Snow, 2015). The high density of occurrences in Europe and North America, particularly for *P. tomentosa*, reflects both successful establishment and local naturalization, indicating that ecological plasticity may also increase invasion risk. In contrast, the concentration of natural populations in East Asia reflects the environmental conditions under which the genus evolved.

This contrast supports the interpretation that the productivity of *Paulownia* is strongly dependent on site-specific growing conditions. Observations obtained from introduced regions cannot be generalized without considering local site characteristics, which helps explain discrepancies in the published data on productivity and stress

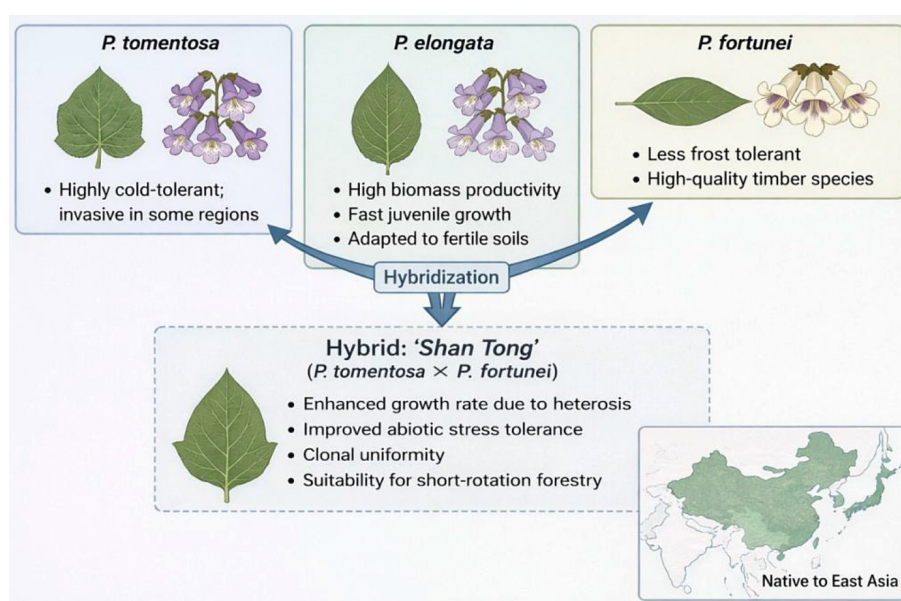


Figure 2. Taxonomic diversity and major species of *Paulownia* used in silviculture, highlighting the origin of the common commercial hybrid 'Shan Tong'

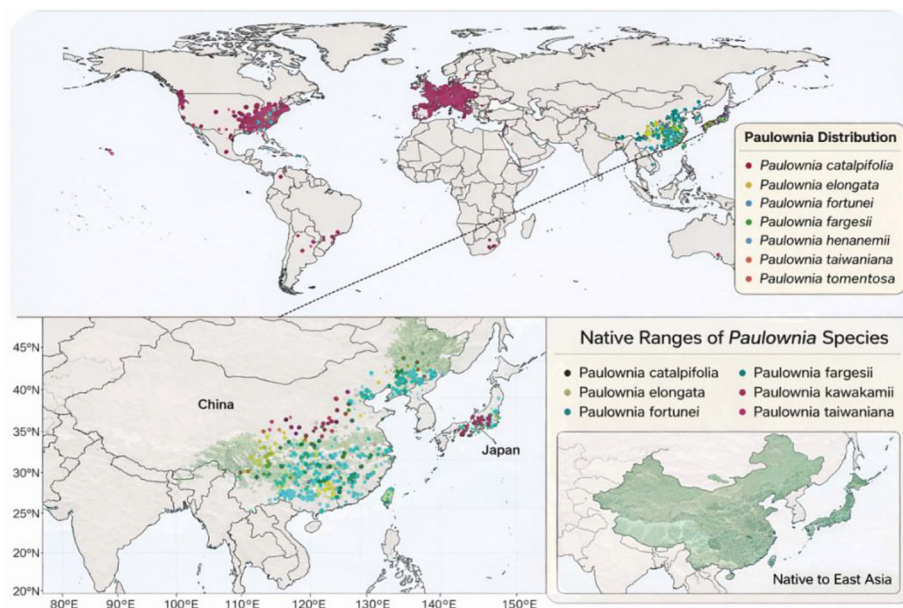


Figure 3. Global distribution and native ranges of major *Paulownia* species based on GBIF occurrence data. The upper panel shows worldwide occurrences across native and introduced regions, while the lower panel highlights the native distribution center in East Asia (primarily China, with extensions into Japan and the Korean Peninsula). The contrast reflects widespread introduction and potential variability in performance outside the native range. (Zhu et al., 1986; Young & Lundgren, 2023)

tolerance (Merriman et al., 2025; Mbarki et al., 2024). Occurrence data for eight *Paulownia* species were obtained from the Global Biodiversity Information Facility (GBIF), while the natural range was expanded to highlight the main centre of diversity in East Asia (Young et al., 2023).

Paulownia tomentosa

Among species of the genus, *Paulownia tomentosa* is distinguished by its exceptional ecological plasticity. This plasticity underlies its ability to establish successfully across a broad range of environmental conditions, but it also accounts for the increased invasion risk reported in several regions outside its native range. In Central Europe, Essl et al. (2007) documented the rapid expansion of populations, particularly in urban and suburban environments. More broadly, invasive plant species have been shown to exhibit greater phenotypic plasticity than native taxa, and this pattern is particularly relevant to *P. tomentosa* (Essl et al., 2007; Nasraoui et al., 2025). At the plant-community level, Lovenshimer et al. (2017) identified measurable changes in vegetation structure and reductions in species richness in areas invaded by this species.

The reproductive ecology of *P. tomentosa* plays a central role in its spread. The production

of large quantities of small, wind-dispersed seeds facilitates rapid colonization of open and disturbed habitats, particularly where competition from established vegetation is limited. This strategy is highly effective in anthropogenically modified landscapes, including roadsides, construction sites, and forest edges.

From a physiological perspective, *P. tomentosa* tolerates a relatively broad range of temperatures, periodic drought, and moderate limitations in nutrient availability. It can establish on compacted or nutrient-poor soils provided that prolonged waterlogging and extreme salinity are absent. These characteristics help explain its extensive naturalization in temperate regions of North America and Europe. At the same time, the limits of this plasticity become evident under edaphic constraints. Increased soil salinity and sodicity impair water uptake and disrupt root-cell membrane functioning, whereas insufficient aeration in heavy clay soils causes hypoxic stress during the early stages of establishment. Under such conditions, plants may still survive, but growth rates decline sharply and wood quality may deteriorate. Consequently, despite its tolerance, *P. tomentosa* is increasingly considered less suitable for large-scale plantation development in regions where its spread cannot be effectively controlled and long-term monitoring cannot be ensured (Snow, 2015).

In contrast, *P. elongata* and *P. fortunei* are more commonly associated with controlled plantation systems and commercial wood production.

Paulownia elongata

Unlike *P. tomentosa*, *Paulownia elongata* is valued primarily for its rapid biomass accumulation and favourable stem form under controlled plantation conditions. *P. elongata* is regarded as a highly productive species because of its rapid early growth and high biomass accumulation under favourable conditions, although its productivity is strongly dependent on soil fertility and suitable site conditions (Vilotić et al., 2015, Mustafazade et al., 2025). Rapid height increment during the early stages of development and relatively straight stems make this species attractive for wood-production systems. However, these advantages are closely associated with site quality and the intensity of management. Despite these advantages, *P. elongata* is sensitive to soil physical properties. In particular, on poorly drained or fine-textured soils, limited oxygen diffusion into the root zone reduces root activity and nutrient uptake. These effects are commonly observed under semi-arid lowland conditions, where periods of irrigation alternate with prolonged drying periods.

Although the species can tolerate short-term periods of water deficit, prolonged drought in the absence of supplemental irrigation results in a pronounced reduction in stem diameter increment and deterioration of wood quality. Salinity further exacerbates these limitations by disrupting ionic balance and reducing physiological activity, even at moderate levels of electrical conductivity. Reports of less frequent spontaneous regeneration for some *P. elongata* material cannot establish low invasive risk across the species. Seed viability, recruitment under local disturbance, and clone identity must be assessed at the introduction site.

Paulownia fortunei

Paulownia fortunei occupies an intermediate position within the genus, combining moderate growth rates with relatively high structural stability. The species is valued for its wood quality and relatively stable growth characteristics. However, its lower frost tolerance and moderate growth rate may limit its cultivation under colder or otherwise unfavourable environmental conditions (Qin et al., 2024). Compared with *P. tomentosa*, these species are generally characterized by straighter

stems, greater wood uniformity, and a lower capacity for spontaneous regeneration, making them more suitable for intensively managed industrial plantations (Barbu et al., 2022; Zhang et al., 2020). Although early-stage growth is generally slower than that of *P. elongata*, the species often produces wood with higher density and more stable mechanical properties (Lee et al., 2024).

From an ecological perspective, *P. fortunei* demonstrates greater tolerance to soil heterogeneity and moderate clay content, provided that basic drainage requirements are met. Its root system appears to be less susceptible to hypoxia-induced dysfunction, which may contribute to improved plant anchorage and stand stability, particularly on alluvial soils or in areas periodically exposed to excessive moisture. Sensitivity to elevated salinity and prolonged waterlogging remains a limiting factor. Under such conditions, growth suppression follows patterns similar to those observed in *P. elongata*, including reduced root respiration and disruption of ionic balance. Nevertheless, relatively limited seed production and weak natural regeneration reduce its potential for uncontrolled spread, making *P. fortunei* a comparatively manageable species under plantation cultivation.

Hybrids and selectively bred Paulownia products

In addition to individual *Paulownia* species, hybrid cultivars and selectively bred planting materials have become increasingly important in commercial plantation systems. These materials are generally developed to combine desirable traits from different species, such as rapid early growth, improved stem form, enhanced wood quality, greater tolerance to drought or low temperatures, and increased biomass production. Their performance, however, is highly dependent on genotype × environment interactions, and traits observed under favourable experimental or plantation conditions cannot necessarily be extrapolated to other climatic and edaphic environments. Commercially selected *Paulownia* hybrids are often promoted on the basis of their high growth rates and biomass productivity. However, the reported performance of such materials may vary considerably depending on planting density, irrigation regime, soil fertility, temperature, and management intensity. Therefore, the ecological and silvicultural characteristics of hybrid materials should be evaluated separately from those of their parental species.

An important consideration is that selective breeding for rapid growth and biomass accumulation may alter other ecological characteristics, including reproductive capacity, stress tolerance, and the ability to regenerate outside managed plantations. Consequently, the assessment of hybrid and selectively bred Paulownia materials should include not only productivity and wood quality but also their potential for naturalization, reproductive behaviour, and environmental adaptability. Despite these advantages, the productive potential of *P. elongata* and *P. fortunei* should not be interpreted as evidence of broad environmental tolerance. Both species may show reduced performance under salinity and poor soil aeration, particularly during early establishment, when elevated soil electrical conductivity and heavy clay content can substantially restrict root development and biomass accumulation (Ayala-Astorga et al., 2009; Georgieva et al., 2018). Field studies conducted under semi-arid conditions similarly indicate that Paulownia species may survive moderate water limitation, whereas growth and biomass production decline considerably when drought occurs in combination with salinity, particularly in sodic soils with restricted drainage (García-Morote et al., 2014; Mbarki et al., 2024). These observations emphasize an important distinction between physiological survival under stress and the maintenance of economically viable productivity.

The contrasting advantages and limitations of individual Paulownia species have stimulated the development of cultivars, selected genotypes, and interspecific hybrids aimed at combining desirable growth, wood-quality, and stress-adaptive traits. A representative example is the widely cultivated hybrid ‘Shan Tong’ (*P. tomentosa* × *P. fortunei*), which combines rapid growth with improved tolerance to certain abiotic stresses (Figure 2). Nevertheless, hybridization can integrate complementary parental traits without necessarily eliminating the ecological limitations inherited from the parental species (Ismail et al., 2024). Therefore, native Paulownia species, selected cultivars, genotypes, and interspecific hybrids should not be regarded as functionally equivalent or as universally applicable planting material under changing environmental conditions. Their performance depends on the interaction between genotype and site-specific factors, including temperature regime, water availability, soil salinity, fertility, texture,

aeration, and drainage. Accordingly, successful Paulownia cultivation requires strategic matching of species and genotypes to the environmental conditions and production objectives of a particular site rather than reliance on generalized assumptions of rapid growth or broad stress tolerance (Jakubowski et al., 2022).

Development and use of interspecific Paulownia hybrids

The ecological and silvicultural limitations observed in pure Paulownia species have prompted extensive efforts toward interspecific hybridization (Li et al., 2020). Hybrid development aims to combine rapid growth, improved stem quality, partial sterility, and enhanced adaptability into genotypes better suited to plantation forestry and the utilization of marginal lands. As a result of decades of breeding efforts, most commercial Paulownia plantations currently established outside East Asia are based on hybrids rather than pure species (Jakubowski, 2022; Lugli et al., 2023). The selection of parental forms for interspecific hybridization in Paulownia considers a combination of economically valuable, morphological, physiological, and ecological traits that enable the desirable characteristics of the parental species to be combined in their hybrid progeny. The main criteria for selecting parental genotypes can be divided into five functional groups.

Growth and productivity traits

This group includes plant height, diameter at breast height (DBH), annual increment, growth rate during the juvenile stages, and biomass accumulation. The selection of parental forms with high growth performance is aimed at producing fast-growing hybrids capable of providing high yields of timber or biomass within a relatively short cultivation period.

Architectural and morphological traits

Selection focuses on stem straightness and form, stem diameter, branching pattern, branch diameter and angle, as well as crown architecture. The development of a straight stem with a minimum number of large lateral branches is particularly important for hybrids intended for industrial timber production, as these characteristics directly affect the yield and quality of merchantable wood.

Wood quality characteristics

Wood density, mechanical strength, uniformity, dimensional stability, and other technological properties are of considerable importance. These parameters determine the potential industrial applications of the resulting wood and are therefore evaluated alongside overall growth rate. High productivity alone is not a sufficient breeding advantage if it is accompanied by deterioration in wood quality.

Tolerance to abiotic stresses

Particular attention is given to frost tolerance, drought and heat tolerance, as well as salinity tolerance and adaptation to unfavourable soil conditions. The selection of genotypes tolerant to different abiotic stresses can expand the potential cultivation range of hybrids and facilitate their use in regions with limited water availability, increased soil salinity, or unfavourable temperature regimes.

This group of traits is particularly important for plantations established on marginal lands.

Biological and ecological characteristics

This group includes resistance to diseases and pests, reproductive capacity, the degree of viable seed production, capacity for vegetative and microclonal propagation, and the stability of valuable genotypic traits. Limited production of viable seed, where it is documented for a specific clone, may reduce the probability of uncontrolled spread beyond plantation boundaries. Vegetative propagation, however, should not be equated with sterility: clonal multiplication produces genetically uniform planting stock but does not automatically suppress flowering or seed set. Reproductive output must therefore be verified clone by clone. At the same time, a high capacity for clonal propagation in promising genotypes enables the large-scale production of genetically uniform planting material while preserving the

Table 1. Origin, production methods, advantages, and limitations of the main interspecific hybrids and commercial clones of the genus *Paulownia*

Hybrid / Clone	Origin	Main advantage	Potential limitations
Shan Tong	<i>P. tomentosa</i> × <i>P. fortunei</i>	Rapid growth and straight stem; combines the adaptability of <i>P. tomentosa</i> with the commercially valuable traits of <i>P. fortunei</i> ; also represents a good feed resource (Ammar et al., 2023)	Productivity remains dependent on site conditions and planting location [Context-specific; verify for named genotype and site]
In Vitro 112 / Oxytree ('Oxi')	<i>P. elongata</i> × <i>P. fortunei</i>	Rapid growth and high wood quality; of interest for timber and biomass production (Koman & Feher, 2020)	Very low wood density compared with <i>P. tomentosa</i> and dependence on vegetative propagation [Context-specific; verify for named genotype and site]
Cotevisa 2 / PWCOT-2	<i>P. elongata</i> × <i>P. fortunei</i>	High biomass productivity and good wood quality (Fos et al., 2023)	Limited comparative physiological data are available in the scientific literature [Context-specific; verify for named genotype and site]
Sun Tzu 11	<i>P. elongata</i> × <i>P. fortunei</i>	Adapted to dry and semi-arid conditions; used as a biofuel resource (Zuazo et al., 2013)	Requires productivity assessment under specific climatic and soil conditions [Context-specific; verify for named genotype and site]
Hybrid 9502	<i>P. fortunei</i> × <i>P. tomentosa</i>	Rapid growth and high wood quality; demonstrates resistance to diseases, frost, and drought (Kadlec et al., 2026)	Adaptability cannot automatically be extrapolated to all regions [Context-specific; verify for named genotype and site]
Hybrid 9503	<i>P. fortunei</i> × <i>P. tomentosa</i>	Characterized by rapid growth and high wood quality, as well as tolerance to a range of stressors	Insufficient comparative information across a broad range of growing conditions [Context-specific; verify for named genotype and site]
Pao-tong Z07	<i>P. fortunei</i> × <i>P. tomentosa</i> × <i>P. kawakamii</i>	Characterized by high frost tolerance, rapid growth, and a cylindrical stem (Kadlec et al., 2026)	More complex genetic background and requires site-specific evaluation [Context-specific; verify for named genotype and site]
Hybrid 9501	(<i>P. fortunei</i> × <i>P. elongata</i>) × (<i>P. fortunei</i> × <i>P. tomentosa</i>)	Combines traits from three species within a complex hybrid genotype	Complex origin makes it difficult to generalize its characteristics without testing the specific clone [Context-specific; verify for named genotype and site]

selected combination of economically valuable traits. Some managed comparisons report favorable growth or stem form in particular hybrids, but genotype identity, site, irrigation, and comparator differ across studies; a general hybrid advantage over parental species has not been established (Jakubowski, 2022).

Selected commercial clones have been used or proposed for dry-region plantations, but claims of adaptation require replicated comparisons with identified parental material and measured water and salinity conditions; the clone names alone do not predict site performance. Hybrids are generally propagated vegetatively, using stem and root cuttings, which represent practical methods for the rapid and large-scale production of Paulownia planting material, particularly for *P. fortunei* and *P. elongata*. Studies have shown that both the type of cutting and the conditions under which it is handled significantly affect shoot formation and rooting success, which are critical for obtaining uniform clonal planting material. Such propagation through cuttings, together with in

vitro propagation, provides a relatively low-cost and scalable approach to plantation establishment (Maqbool et al., 2024).

Role of Paulownia in plantations under environmental stress

Differences between Paulownia species and hybrids have direct implications for sustainable land-use planning in semi-arid regions and areas affected by soil salinity. Pure species lines, particularly *P. tomentosa*, pose a higher ecological risk due to their reproductive characteristics and are therefore avoided in regions where natural regeneration cannot be effectively controlled (Essl et al., 2007; Snow, 2015). In contrast, vegetatively propagated hybrids represent a more manageable option for commercial use and land restoration purposes. Previous studies indicate that Paulownia cannot be regarded as a taxonomically or ecologically uniform genus, and its growth depends on a range of factors. For this reason, successful utilization requires genotype-specific selection,

Table 2. Comparative ecological and silvicultural characteristics of major Paulownia species

Parameters	<i>P. tomentosa</i>	<i>P. elongata</i>	<i>P. fortunei</i>
Growth strategy	Opportunistic, colonization-oriented	Productivity-driven under managed conditions	Balanced growth with structural stability [Context-specific; verify for named genotype and site]
Juvenile growth rate	Moderate to high	Very high	Moderate [Context-specific; verify for named genotype and site]
Reproductive capacity	Very high (abundant, wind-dispersed seeds)	Low	Low to moderate [Context-specific; verify for named genotype and site]
Natural regeneration	Frequent and self-sustaining	Rare	Rare [Context-specific; verify for named genotype and site]
Invasive potential	High	Very low	Very low [Context-specific; verify for named genotype and site]
Soil texture tolerance	Broad, except extreme salinity or waterlogging	Low (compacted/clay soils)	Moderate (adequate drainage) [Context-specific; verify for named genotype and site]
Salinity tolerance	Low to moderate	Low	Low [Context-specific; verify for named genotype and site]
Drought tolerance	Moderate	Low to moderate (management-dependent)	Moderate [Context-specific; verify for named genotype and site]
Waterlogging tolerance	Low	Very low	Low [Context-specific; verify for named genotype and site]
Root system characteristics	Rapid early expansion, shallow	Highly sensitive to hypoxic conditions	Robust, mechanically stable [Context-specific; verify for named genotype and site]
Dependence on management	Low	High	Moderate [Context-specific; verify for named genotype and site]
Suitability for plantation forestry	Limited (ecological/invasion risk)	High under controlled conditions	High under broad managed conditions [Context-specific; verify for named genotype and site]
Role in hybridization programs	Donor of ecological adaptability traits	Donor of rapid growth traits	Donor of structural stability and stress moderation traits [Context-specific; verify for named genotype and site]

detailed assessment of soil and water conditions, as well as management strategies adapted to local edaphic constraints (Bergmann et al., 2019; Meriman et al., 2025).

Table 2 is an unweighted, qualitative interpretation of reported traits, drawing on Zhu et al. (1986), Essl et al. (2007), García-Morote et al. (2014), Snow (2015), Jakubowski (2022), and Georgieva et al. (2018). Its descriptors of tolerance, productivity, and invasion risk are not validated comparative scores. Field outcomes, controlled stress responses, and occurrence or reproductive evidence have different scopes and should not be treated as interchangeable. Although Table 2 summarizes species-specific responses to adverse environmental conditions, a broader comparison of the principal stress factors is presented in Table 3.

PERFORMANCE AND BIOECONOMIC APPLICATIONS OF PAULOWNIA

Bibliometric evidence confirms a strong expansion and diversification of Paulownia research since 1971, with recent thematic shifts toward bioenergy/biochar and genomics alongside traditional timber and taxonomy lines (Lugli et al., 2023). Beyond timber production, the industrial relevance of Paulownia extends to functional materials and integrated biorefineries (Amirli et al., 2026). Its low-density cellular structure, workability, cellulose-rich chemistry, extractives, and capacity to generate porous carbon materials

create several product routes, while also imposing application-specific limitations. Figure 5 provides a conceptual overview of these linked domains and emphasizes that feedstock quality is shaped upstream by genotype, site, and management.

The figure summarizes major classes of secondary metabolites (e.g., flavonoids, phenylpropanoids, terpenoids, and polysaccharides) and their linkage to functional products, including food, feed, pharmaceuticals, cosmetics, and carbon-based materials (Zhang et al., 2020; Alagawany et al., 2022). The schematic representation is qualitative and intended to highlight application pathways rather than quantitative contribution of individual components. Recent plywood-focused work indicates that pure Paulownia plywood tends to show lower stiffness/strength and more surface defects than poplar-based panels, while mixed poplar–Paulownia configurations can approach poplar performance when Paulownia is used mainly in inner plies (Nocetti et al., 2025). Among these application domains, wood production remains the most established pathway; however, its performance under semi-arid and saline conditions is governed by distinct trade-offs between growth rate, structural quality and functional suitability.

Growth dynamics and yield variability: why reported productivity differs so widely

Reported Paulownia productivity varies widely among studies, but values expressed for different biomass fractions, ages, rotation lengths,

Table 3. Responses of Paulownia species and hybrids to major environmental stress factors and their implications for plantation

Extreme factor	Experimental conditions	Main response of Paulownia	Practical implication
Drought	Soil moisture: 75% → 55 → 40 → 25%	Decreased RWC, chlorophyll content, and growth. Autotetraploid <i>P. tomentosa</i> × <i>P. fortunei</i> was more tolerant than the diploid form	Moderate drought tolerance; strong dependence on genotype and ploidy [Context-specific; verify for named genotype and site]
Salinity	100–150 mM NaCl, 10–25 days	At 150 mM NaCl, <i>P. tomentosa</i> × <i>P. fortunei</i> maintained adaptation, whereas the treatment was lethal to <i>P. elongata</i> × <i>P. elongata</i>	Salinity tolerance is strongly genotype-dependent [Context-specific; verify for named genotype and site]
Extreme temperatures	Overall range of approximately –25 to 47°C	Frost tolerance varies: <i>P. tomentosa</i> ≈ –20°C; <i>P. elongata</i> ≈ –15 to –18°C; <i>P. fortunei</i> ≈ –5 to –10°C	Species/hybrid selection according to climatic conditions is required [Context-specific; verify for named genotype and site]
Waterlogging / hypoxia	Universal quantitative thresholds have not been established	Water stagnation and O ₂ deficiency suppress root system functioning	Well-drained soils are required; prolonged waterlogging should be avoided [Context-specific; verify for named genotype and site]

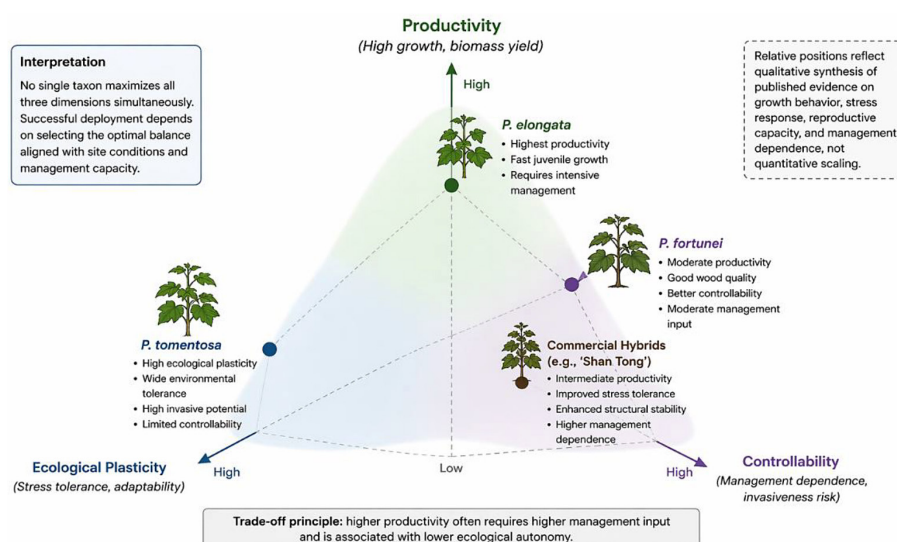


Figure 4. Trade-offs among major Paulownia taxa in ecological plasticity, productivity, and controllability. *P. tomentosa* shows high plasticity but low controllability, *P. elongata* maximizes productivity under intensive management, while *P. fortunei* and hybrids occupy intermediate positions

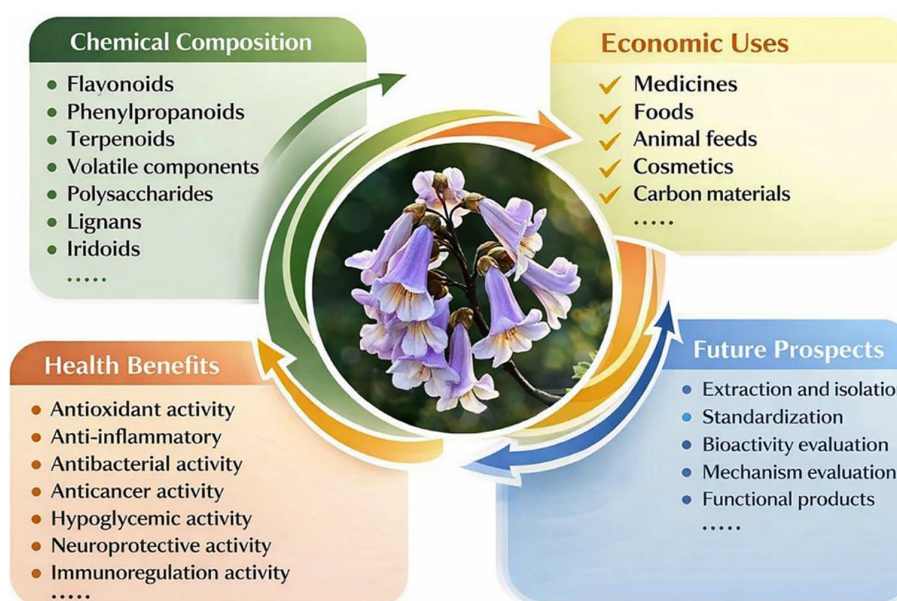


Figure 5. Conceptual overview of the industrial and bioeconomic potential of Paulownia, illustrating the interconnections between chemical composition, health-related bioactivities, economic uses, and future biorefinery-oriented applications

moisture bases, and areas cannot be read as a common yield distribution. Within individual field trials, soil, irrigation, planting stock, and management plausibly explain part of the variation; a quantitative cross-study attribution was not conducted. A global synthesis of plantation data encompassing 121 observations from 21 sites revealed that maximum yields are almost exclusively associated with irrigated plantations established on deep, well-drained soils and

managed through pruning, coppicing, and fertilization (Merriman et al., 2025). In contrast, sites lacking irrigation or suffering from compaction and shallow rooting depth showed early stagnation, despite initially rapid height growth. This phenomenon explains why early promotional claims based on short-term trials often overestimate long-term productivity.

In semi-arid Mediterranean environments, where water availability is a primary limiting

factor, productivity stabilizes at more moderate but still relevant levels. García-Morote et al. (2014) demonstrated that *Paulownia elongata* × *P. fortunei* maintained 2.14–4.50 t ha⁻¹ yr⁻¹ of stem biomass under low irrigation regimes, confirming that growth does not collapse under water restriction but adjusts to available resources. Importantly, these yields were achieved without intensive fertilization, highlighting the role of root development and efficient canopy formation rather than nutrient-driven growth alone. However, when Paulownia is planted on truly marginal or degraded soils, expectations must be recalibrated. Trials in Spain comparing *P. fortunei* with *Eucalyptus globulus* showed that Paulownia yielded only 3.34 t ha⁻¹ over three years, whereas eucalyptus exceeded 40 t ha⁻¹ under the same conditions. This contrast underscores that Paulownia is not universally superior to established fast-growing species, particularly where soil constraints dominate growth outcomes.

Stand design and management determinants of productivity

The rapid early development of Paulownia is closely linked to its growth strategy, which emphasizes swift canopy formation and stem elongation during the establishment phase. By investing heavily in leaf area expansion, young trees maximize light interception and carbon assimilation, enabling height increments of 3–5 m yr⁻¹ within the first few growing seasons under favorable conditions. In intensively managed plantations, even higher values have occasionally been recorded (Zhu et al., 1986; Merriman et al., 2025). Diameter growth follows a comparable trajectory, reflecting high rates of cambial activity and efficient internal water transport.

Despite this early vigor, long-term productivity varies markedly among sites. Yield assessments consistently show that performance is highly contingent on soil quality, water availability, and management intensity. Mean annual increment values may remain below 2 odt ha⁻¹ yr⁻¹ in marginal environments, while exceeding 20 odt ha⁻¹ yr⁻¹ in systems supported by irrigation, fertilization, and careful spacing (García-Morote et al., 2014; Merriman et al., 2025; Merriman et al., 2025). Such divergence highlights the limited capacity of Paulownia to buffer against suboptimal conditions.

Biomass accumulation is strongly concentrated in the initial rotation. The first 5–7 years account for most stem volume production, after which growth slows as competition for light intensifies and physiological constraints associated with tree height become more pronounced. Although coppicing stimulates regrowth, subsequent cycles generally yield less than the initial establishment phase, particularly where soil moisture or nutrient reserves decline over time. Planting density introduces further trade-offs. Dense stands favor rapid site capture and short-term biomass output but produce slender stems with reduced structural stability and lower timber quality. Wider spacing promotes diameter development and higher-value wood but limits early biomass accumulation per unit area. Optimal configurations therefore depend on whether the production goal prioritizes energy feedstock or solid wood products.

Some field experiments report substantial biomass reductions as irrigation is reduced (García-Morote et al., 2014). With few comparable treatment levels and differing genotypes and sites, these results do not establish a common nonlinear breakpoint; controlled salinity and drainage studies should likewise not be extrapolated to a field threshold. Paulownia wood can be valorized not only through traditional timber and pulp uses but also as a high-yield feedstock for biochar production (Vaughn et al., 2017). Biochar produced from Paulownia elongata shows inherently high carbon content and desirable pore structure for horticultural substrates, even without chemical activation (Vaughn et al., 2017). In controlled experiments, oxidative treatments with sulfuric acid, oxalic acid, and hydrogen peroxide did not improve physical or chemical metrics such as surface area or cation exchange capacity, indicating that unmodified Paulownia biochar may already possess suitable characteristics for greenhouse root media and peat substitution. Mineral-enhanced treatments, such as liming biomass prior to pyrolysis, have demonstrated increases in carbon capture capacity and surface reactivity, suggesting that biomass pre-processing techniques are a promising route for optimizing biochar quality for climate mitigation and soil applications. In broader context, biochar amendments consistently improve substrate water holding capacity, nutrient availability, and tree tolerance to environmental stress, enhancing establishment success and promoting soil restoration in degraded landscapes.

Species versus hybrids under semi-arid and salt-affected soils

Selected hybrid trials under managed semi-arid conditions report useful productivity, but direct, replicated comparisons with pure species under matched salinity, irrigation, soil, and age are insufficient to infer that hybrids generally outperform pure species (García-Morote et al., 2014; Jakubowski, 2022). However, the advantages conferred by hybrid vigor are not sufficient to overcome severe edaphic constraints. In heavy clay soils with high electrical conductivity and poor aeration, both species and hybrids experience reduced growth rates, impaired nutrient uptake, and declining wood quality (Georgieva et al., 2018; Ayala-Astorga et al., 2009). These results demonstrate that hybridization mitigates – but does not eliminate – the fundamental limitations imposed by salt-affected soils. Crucially, the reviewed literature shows that performance variability among hybrids can exceed that observed among species, underscoring the need for site-specific trials and genotype screening rather than generalized recommendations.

Water relations and drought response

Paulownia is frequently described in both scientific and applied literature as a drought-tolerant tree; however, detailed physiological evidence does not support this classification in a strict sense. Rather than exhibiting intrinsic drought tolerance, Paulownia relies on a strategy better described as drought avoidance mediated by high physiological efficiency (Zhu et al., 1986; Merriman et al., 2025). This distinction is critical for understanding both its apparent success under moderate water limitation and its abrupt failure under prolonged drought conditions. During early and mid-season growth, Paulownia invests heavily in rapid leaf expansion, producing large leaves (15–30 cm) that maximize photosynthetic surface area and carbon assimilation during periods of adequate soil moisture (Zhu et al., 1986). Simultaneously, the development of a predominantly vertical root system capable of reaching depths of 2.5–5.0 m enables temporary access to subsoil water reserves in well-structured soils (García-Morote et al., 2014; Merriman et al., 2025). These traits support rapid biomass accumulation during favorable moisture windows rather than sustained growth under continuous stress (Zhu et al., 1986; García-Morote et al., 2014; Merriman et al., 2025).

Water-use assessments further clarify this strategy. Seasonal water consumption (430–610 L per tree) falls within the range of other fast-growing hardwoods, contradicting claims of exceptionally low water demand (Baier et al., 2021; Durán Zuazo et al., 2013). However, when normalized to biomass production, Paulownia often exhibits relatively high water-use efficiency during the juvenile phase, particularly under semi-arid conditions (García-Morote et al., 2014). At the physiological level, selected hybrids such as ‘Shan Tong’ demonstrate the ability to maintain photosynthetic activity at leaf water potentials approaching -9.2 MPa (Fkiri et al., 2025). This response is associated with tight stomatal regulation, which delays excessive xylem tension and reduces embolism risk. Importantly, this mechanism reflects regulatory control rather than structural drought adaptation, as anatomical traits remain characteristic of mesophytic species (Young & Lundgren, 2023).

Stomatal closure and reduced growth during water limitation are physiologically plausible and documented under particular treatments. The cited field evidence does not resolve a universal soil-moisture breakpoint or show that productivity always collapses abruptly (García-Morote et al., 2014). From a management perspective, irrigation timing is more critical than total water input. Early-season irrigation during leaf expansion and stem elongation sustains productivity, whereas delayed water supply provides limited benefit (García-Morote et al., 2014). Conversely, prolonged water deficits can result in irreversible growth suppression within a single season.

This efficiency-driven strategy also involves hidden costs. Large leaf surfaces increase transpirational demand and thermal stress, making Paulownia highly sensitive to heat waves under low soil moisture (Zhu et al., 1986). In compacted or poorly aerated soils, restricted root development further amplifies drought sensitivity, leading to establishment failures and early mortality rates of 20–40% in unmanaged conditions (García-Morote et al., 2014; Merriman et al., 2025). The available evidence supports cautious site-specific water management, especially during establishment. Drought responses should be reported for a named genotype, soil, age, measurement method, and observation period; a genus-wide classification or threshold remains unsupported.

Salinity response and physiological limits

Paulownia species are often reported to persist under saline and semi-arid conditions; however, this capacity does not reflect true halophytic behavior. Instead, tolerance within the genus is conditional and strongly genotype-dependent, arising from physiological regulation and morphological plasticity rather than specialized salt-adaptive mechanisms (Ayala-Astorga et al., 2009; Youssef et al., 2020). Salinity can suppress growth through osmotic and ionic stress, as shown in controlled exposures for particular Paulownia material (Ayala-Astorga et al., 2009; Youssef et al., 2020). NaCl concentration in culture media and soil electrical conductivity describe different exposure conditions and should not be converted into a common field tolerance limit without method-specific data.

Responses of particular hybrids in controlled experiments suggest variation among genotypes, but do not demonstrate a general advantage for hybrids containing *P. fortunei* genetics under field salinity. Matched, replicated field comparisons are needed. Physiological responses to combined drought–salinity stress further constrain performance. Salinity exacerbates water stress by reducing soil water availability and impairing root function, leading to reduced nutrient uptake and disruption of metabolic processes. Under such conditions, survival may be maintained, but productive growth declines sharply.

García-Morote et al. (2014) reported stem biomass yields of 2.14–4.50 t ha⁻¹ yr⁻¹ for *P. elongata* × *P. fortunei* under low irrigation at the studied field site. These water-limited yields should not be presented as evidence for production on saline soil unless soil EC and its measurement protocol were documented in the same experiment. Integrated management approaches, including soil amendments such as compost and improved drainage, have been proposed to mitigate salinity effects while supporting biomass production and soil rehabilitation (Madejón et al., 2016). However, such interventions increase system complexity and reinforce the dependence of Paulownia on active management. Paulownia responses to salt exposure depend on genotype, age, medium, duration, and the measurement of salinity. Current evidence supports caution at candidate sites but does not establish a physiological or economic soil-EC cutoff applicable across species or regions.

Biomass composition and energy performance: promise with important caveats

From an energy and materials perspective, Paulownia biomass occupies an ambiguous position between attractive chemical composition and unfavorable physical properties. Recent compositional analyses consistently report high cellulose contents (43–48 wt%) and relatively low lignin fractions (20–24 wt%) in Paulownia wood, values that are favorable for biochemical conversion pathways but less optimal for direct thermochemical energy use (López et al., 2012; Rodríguez-Seoane et al., 2020). Hemicellulose content typically ranges between 18 and 23 wt%, contributing to rapid thermal degradation but also increasing volatility during combustion (López et al., 2012). Paulownia has also been evaluated as a dual-purpose feedstock for solid biofuel production and cellulose pulp, highlighting its potential in integrated bioeconomy value chains (López et al., 2012).

On a mass basis, the gross calorific value (GCV) of Paulownia biomass generally falls within 19.2–19.7 MJ·kg⁻¹, which is comparable to that of willow and poplar and well within the range of accepted bioenergy feedstocks (Pożoga, et al., 2019, Joshee, et al., 2012). However, this apparent competitiveness masks a critical limitation: exceptionally low basic wood density, typically 230–300 kg·m⁻³ for juvenile material and rarely exceeding 350 kg·m⁻³ even in mature stems (Merriman et al., 2025). As a result, volumetric energy density is substantially lower than that of conventional energy crops, reducing transport efficiency and storage economy.

This density constraint becomes particularly evident in pelletization and densification studies of woody stems. Importantly, Table 4 does not describe wood-fuel pellets. It reports physical properties of *P. elongata* leaf-based pellets formulated as an animal-feed resource at two blending ratios (75% and 95% Paulownia; n = 10) (Stewart et al., 2018). Those data are retained here only as a documented example of densified Paulownia biomass from leaves; they cannot be used to infer compliance of stem-wood fuel pellets with solid-biofuel standards. For energy pellets, published work instead indicates that juvenile stem material frequently underperforms denser hardwoods because of low basic density

and thin cell walls, and that blending with higher-density residues is often required to improve handling properties (Rodríguez-Seoane et al., 2020; Merriman et al., 2025).

The leaf-feed pellet measurements in Table 4 do not allow assessment of wood-fuel pellet compliance. The statements about widespread failure of Paulownia wood pellets to meet graded-fuel specifications cannot be established from the sources cited here and should be tested using wood-derived pellets, specified process conditions, and the applicable standard and class. Blending denser residues with Paulownia wood may improve volumetric properties, but a general 30–50% blending optimum or durability above 97% is not supported by the cited leaf-feed and plantation studies. Wood-pellet trials should report feedstock part and moisture, blend composition, die conditions, bulk density, mechanical durability, ash, and the tested standard.

Recent system-level analyses therefore converge on a consistent conclusion – Paulownia is poorly suited as a stand-alone solid biofuel, particularly when stems from short-rotation plantations are used directly. Instead, its more defensible role lies within integrated biomass value chains, where low-density material is valorized as a secondary feedstock, combined with higher-density residues, or redirected toward biochemical and biorefinery pathways. Some reviews argue that cascading use – wood products first, energy recovery from residues later—can improve system efficiency relative to energy-only utilization (Merriman et al., 2025). Dedicated, transparent life-cycle assessments and techno-economic analyses for Paulownia remain limited, however, and claims that biorefinery routes are invariably more profitable should be treated as hypotheses until site- and process-specific studies are available.

Functional materials and engineered wood products

Paulownia wood combines very low density with favorable dimensional stability, a comparatively uniform texture, and easy machining. These attributes should not be interpreted as evidence of universal structural performance. Rather, they define a lightweight material platform whose suitability depends on matching density, anatomy, and mechanical properties to the intended product. Reported basic density commonly lies near 230–350 kg m⁻³, and juvenile material may show substantial radial and site-related variability in vessel dimensions, fiber geometry, and strength (Akyildiz & Kol Sahin, 2010; Vilotić et al., 2015; Barbu et al., 2022; Fos et al., 2023). Consequently, plantation age, growth rate, spacing, and water regime are material-quality variables, not merely silvicultural descriptors.

For solid-wood uses, the low mass and dimensional stability of Paulownia are advantageous in products where weight reduction, insulation, ease of handling, and resistance to warping are more important than high load-bearing capacity. Potential uses include furniture components, interior joinery, packaging, lightweight cores, musical and craft products, and non-load-bearing elements. The principal limitation is comparatively low stiffness, hardness, and fastener-holding capacity. Material selection and grading are therefore essential, and claims based on rapid stem growth should not be extrapolated directly to structural performance without mechanical testing of the relevant genotype, age class, and site (Akyildiz & Kol Sahin, 2010; Barbu et al., 2022).

Engineered panels provide a more flexible route because Paulownia can be positioned where its low density is beneficial and stronger veneers or fibers can carry the principal loads. Recent plywood evidence shows that all-Paulownia panels

Table 4. Mean physical properties of *P. elongata* leaf-based animal-feed pellets (Stewart et al., 2018; n = 10).

Properties	75% Paulownia (mean ± S.E.)	95% Paulownia (mean ± S.E.)
Length, mm	36.4 ± 0.72 ^a	32.77 ± 1 ^b
Diameter, mm	3.59 ± 0.01 ^a	3.59 ± 0.01 ^a
Unit weight, g	0.72 ± 0.06 ^a	0.71 ± 0.01 ^a
Unit density, kg·m ⁻³	1958.05 ± 42.8 ^a	2164.96 ± 66.51 ^b
Bulk density, kg·m ⁻³	557.21 ± 7.56 ^a	596.1 ± 7.14 ^b
Hardness, N	31.65 ± 0.23 ^a	34.36 ± 0.23 ^b

Note: These values refer to feed formulations, not to wood-fuel pellets. Means within a row that share a letter are not significantly different at $p < 0.05$

tend to have lower bending stiffness and strength and more surface defects than poplar plywood, whereas mixed poplar–Paulownia layups can approach poplar performance when Paulownia is concentrated in the inner plies (Nocetti et al., 2025). This indicates a realistic design strategy: use Paulownia as a lightweight core or intermediate layer rather than assume direct substitution for denser species. The same principle is relevant to sandwich panels and hybrid composites, although adhesive compatibility, veneer quality, moisture cycling, fire behavior, and long-term durability require systematic validation.

The chemical composition of Paulownia also supports fiber-based products. Cellulose contents of approximately 43–48 wt% and relatively low lignin contents of about 20–24 wt% facilitate pulping and fiber liberation, while short rotation times may provide a regular feedstock supply (Caparrós et al., 2008; López et al., 2012; Rodríguez-Seoane et al., 2020). Nevertheless, pulp yield and paper performance depend on fiber length, cell-wall thickness, extractives, and pretreatment conditions. Paulownia is therefore better evaluated as a blend component or specialized fiber source than promoted as an automatic replacement for established pulpwoods. Comparative trials should report drainage, tensile and tear indices, brightness, chemical demand, and recovery performance alongside simple delignification yield.

Thermochemical conversion extends the materials portfolio beyond wood products. Paulownia-derived biochar has high carbon content and a porous structure suitable for horticultural substrates, peat replacement, and soil-conditioning formulations. Vaughn et al. (2017) found that unmodified *P. elongata* biochar already possessed useful physical characteristics, while oxidative modification did not consistently improve surface area or cation-exchange performance. This result is important for process design because additional chemical treatment should be justified by a measurable functional gain. Biochar quality must also be evaluated against feedstock part, pyrolysis temperature, ash chemistry, contaminant content, water retention, nutrient interactions, and stability rather than inferred from carbon content alone.

Taken together, the materials evidence favors application-specific and cascading use. Higher-quality stems can enter lightweight wood and hybrid-panel products; suitable fiber fractions can be directed to pulp or composite manufacture; and bark, fines, pruning residues,

and end-of-life fractions can be converted to biochar, chemicals, or energy. This hierarchy retains material value before final energy recovery and offers a stronger rationale than an energy-only plantation model. However, robust comparison requires harmonized reporting of genotype, plantation conditions, density, anatomy, mechanical properties, durability, processing yield, and product standards. Without that chain of evidence, variability generated during cultivation remains hidden until manufacturing.

Biorefinery applications – laboratory feasibility and scale-up needs

Paulownia wood has been investigated in hydrothermal, solvent-based, and fermentation routes, making integrated biorefinery a plausible research direction. Laboratory conversion outcomes do not yet establish its industrial advantage over other hardwoods; feedstock-matched comparative balances and scale-up evidence are required. Rodríguez-Rebelo et al. (2024) investigated deep eutectic solvent fractionation of Paulownia wood. Any reported delignification or cellulose-retention percentage must be interpreted for that study's stated species or clone, wood fraction, solvent composition, temperature, duration, solid loading, and analytical denominator. The previously stated 94% lignin removal and 93% cellulose retention are not treated here as transferable performance benchmarks or as evidence of superiority over organosolv or alkaline processes without matched comparative trials.

Reported saccharification and ethanol outcomes arise from distinct Paulownia pretreatment and fermentation experiments (Rodríguez-Rebelo et al., 2024; Domínguez et al., 2017). Glucose conversion, ethanol concentration, and percent theoretical yield use different denominators and experimental conditions; the previously quoted 85–90%, 43.6 g L⁻¹, and 89.7% should only be reinstated after confirming the exact Paulownia feedstock, process, and basis in each primary paper. These experiments establish feasibility, not consistently high yields across feedstocks or superiority over other hardwoods. Lignin recovery and aromatic-product yields are process-specific. The previously stated approximately 84% lignin purity and syringaldehyde and vanillin quantities (approximately 25 and 10 mg g⁻¹ lignin) should not be generalized to Paulownia DES lignin: each value requires confirmation in the cited primary

paper of species or hybrid, plant part, extraction and depolymerization steps, and yield denominator (Rodríguez-Seoane et al., 2021; Lee et al., 2024). No advantage of drought- or salinity-grown material can be inferred from these unpaired laboratory studies.

Hydrothermal treatment of Paulownia wood and extraction of other plant fractions demonstrate possible separate product streams (Del-Río et al., 2022; Rodríguez-Seoane et al., 2021). The different feedstocks and conditions cannot establish an integrated commercial yield or environmental benefit. Comparative life-cycle assessment depends on explicit system boundaries, energy inputs, coproduct allocation, and local alternatives. A complete biorefinery assessment must also consider feedstock heterogeneity. Stem wood is the principal source of cellulose-rich solids, whereas bark, leaves, and petioles contain different proportions of ash, extractives, phenolics, and structural carbohydrates. Keeping these streams separate can improve process control: clean wood fractions can be prioritized for pulping or carbohydrate conversion, extractive-rich foliage can enter targeted recovery routes, and residual solids can be carbonized or used for process energy. Such fraction-specific routing reduces the risk that a single low-value or ash-rich stream compromises the quality of all outputs (Rodríguez-Seoane et al., 2021; Rodríguez-Seoane et al., 2020).

Before evaluating an integrated Paulownia biorefinery, studies should report mass and energy balances, solvent and water recovery, inhibitors, enzyme and chemical inputs, lignin purity, coproduct outlets, and site-specific life-cycle and techno-economic analyses. A paired comparison of stressed and unstressed trees of the same genotype and age is also needed to test whether growing conditions alter subsequent processing yields. Current studies support the technical possibility of obtaining multiple fractions from Paulownia biomass. Cascading use is a promising design hypothesis, but neither industrial superiority nor a process advantage specific to biomass grown under drought or salinity has been demonstrated by the available laboratory results.

Practical implications, policy considerations, and deployment guidelines

The preceding sections demonstrate that Paulownia can deliver high functional performance under well-defined conditions, but that this

performance is neither universal nor self-sustaining without appropriate management. Translating these findings into practice therefore requires careful alignment between site characteristics, management capacity, and intended end-use pathways. This section synthesizes current evidence into applied considerations aimed at supporting realistic, risk-aware deployment of Paulownia-based systems.

Site selection and land suitability

Good drainage, root-zone conditions, and reliable water access are reasonable screening criteria for candidate plantations. The previously cited soil EC interval of 6–8 dS m⁻¹ combines non-equivalent genotypes and measurement conditions and must not be used as a physiological or economic threshold. Measure and report whether EC is from a saturated-paste extract or another soil-to-water ratio, sampling depth, season, and associated sodicity; evaluate growth and survival in local pilot plots before setting a site-specific limit. Accordingly, Paulownia should not be promoted as a remediation species for highly saline or structurally degraded soils without prior soil improvement. Where marginal lands are targeted, deployment should be preceded by drainage enhancement, soil structure amelioration, and realistic yield expectations. Treating Paulownia as a “last-resort” species for severely degraded land risks both plantation failure and reputational damage to afforestation programs.

Management intensity and infrastructure requirements

Contrary to its frequent portrayal as a low-input tree, Paulownia functions most effectively within intensively managed systems. Early establishment success depends on precise irrigation scheduling, adequate nutrient availability, and protection from early-stage stress. In semi-arid environments, irrigation timing has been shown to exert a greater influence on yield than total annual water input, emphasizing the importance of management competence over climatic averages. These requirements position Paulownia closer to agricultural cropping systems than to conventional forestry. As such, deployment should be restricted to contexts where irrigation infrastructure, technical oversight, and long-term management commitment are available. Attempts to

establish Paulownia under extensive or low-input frameworks are unlikely to achieve projected outcomes and may reinforce misconceptions regarding species unreliability.

Species and hybrid selection

Documented invasive behavior of *P. tomentosa* in some introduced regions warrants precautionary screening. Risk for other species and commercial clones cannot be ranked reliably without clone-specific seed production, viability, recruitment, and regional habitat data (Essl et al., 2007; Snow, 2015; Kadlec et al., 2026).

For any proposed species or hybrid, obtain verified identity, assess fertility and seed-based regeneration, inspect surrounding habitats, and monitor escapes. An absence of widely published invasion records for a clone is insufficient to classify it as non-invasive or recommend it without local assessment.

End-use alignment and value-chain integration

Intended end use can guide the planting design and the measurement of wood quality. Wood and panel studies support selected lightweight applications, while laboratory biorefinery experiments suggest possible conversion routes; evidence does not establish a general economic ranking of cascading use against energy-only systems. Investment choices should follow site-specific yields, product testing, comparative mass and energy balances, solvent recovery, life-cycle assessment, and techno-economic analysis. Pilot projects can evaluate durable products and residue conversion together before claiming disproportionate value or policy priority.

Carbon and sustainability considerations

From a climate perspective, Paulownia should be framed as a conditional carbon sink rather than a universal mitigation solution. High early-stage carbon uptake can contribute meaningfully to short-term sequestration goals, but long-term benefits depend on rotation length, harvest frequency, and product lifespan. Carbon accounting frameworks should therefore emphasize net system-level outcomes rather than gross annual uptake figures. In sustainability assessments, ecosystem services such as erosion

control, microclimate regulation, and soil improvement should be considered co-benefits rather than guaranteed outcomes. These services are strongly site- and management-dependent and may diminish under intensive harvesting or suboptimal conditions.

Toward evidence-based deployment strategies

Taken together, available evidence supports the deployment of Paulownia only within clearly defined ecological and managerial envelopes. When these conditions are met, Paulownia can function as a high-performance component of integrated land-use and bioeconomy systems. When they are ignored, the likelihood of ecological risk, economic loss, and policy backlash increases substantially. Effective deployment therefore requires moving beyond promotional narratives toward evidence-based frameworks that explicitly recognize limits, trade-offs, and uncertainties. Such realism does not diminish the value of Paulownia; rather, it provides the foundation for its credible and sustainable use.

REGIONAL CASE STUDY: SUITABILITY OF PAUOWNIA CULTIVATION IN AZERBAIJAN

Azerbaijan offers contrasting candidate environments for site-screening hypotheses: semi-arid, locally salt-affected soils in Hajiqabul and alluvial Kura floodplain soils. The available regional evidence describes climate, soils, and hydrology rather than replicated Paulownia growth, survival, or wood-property measurements at these sites; consequently, neither region has confirmed cultivation suitability.

Hajiqabul District – major soil constraints

Hajiqabul lies within the Kura–Araz Lowland and has a subtropical semi-desert climate characterized by mild winters, hot and dry summers, a mean annual temperature of approximately 12.5–14.6 °C, and annual precipitation of only 215–310 mm. Groundwater commonly occurs at a depth of 3–5 m, while carbonate contents may reach 10–15%. The district contains a heterogeneous soil cover that includes chestnut, grey, meadow-grey,

solonetzic, saline, alluvial-meadow, and solonchak soils. Representative grey soils are alkaline (approximately pH 8.0–8.3), contain little organic matter (about 1.4% humus in the 0–19 cm layer, decreasing with depth), and may contain exchangeable sodium equivalent to 8–15% of cation-exchange capacity. Meadow-grey soils may reach pH 8.6 in the surface layer and show weak solonetzic features below approximately 40–50 cm, with salts accumulating mainly between 25–30 and 80–100 cm (Mammadov, 2007; Salayev, 1991).

The scale of degradation is agronomically important. Compiled figures from Azerbaijani soil inventories indicate that of approximately 22,013 ha of irrigated land assessed in Hajiqabul, 10,909 ha (49.6%) were saline; most of this saline area was classified as weakly saline (84.3%), whereas 14.7% was moderately and 1.0% severely saline. In addition, 38,585 ha, or 23.5% of the district area evaluated, was affected by erosion, and severe erosion represented the largest share of the eroded land (Mammadov, 2007; Salayev, 1991). These compiled district statistics should be re-checked against the original tables and survey year in those monographs before they are used for operational land allocation. These conditions do not exclude Paulownia cultivation everywhere, but they make broad, unqualified plantation recommendations inappropriate. Candidate sites require plot-level measurement of electrical conductivity, exchangeable sodium percentage or sodium adsorption ratio, soil texture, infiltration, drainage, and seasonal groundwater depth. Where reclamation is technically and economically feasible, drainage improvement, controlled leaching, organic amendments, and carefully scheduled irrigation should precede establishment.

Kura River floodplain and tugay soils – comparatively higher potential

Reported soil properties of Kura tugay sites, including pH of about 7.3–7.9 and depth-dependent humus content (Mammadov, 2007), may motivate trial-site selection. They do not demonstrate Paulownia establishment or yield. Seasonal inundation, shallow groundwater, and root-zone oxygen supply require measurement within each trial before any relative suitability claim can be tested.

Deployment implications for Azerbaijan

A testable regional hypothesis is that selected, adequately drained Kura sites may outperform saline Hajiqabul sites under comparable planting and irrigation. Pilot trials should use genetically identified material and local controls, assess clone-specific reproductive risk, record EC method and depth, sodicity, groundwater and irrigation, and measure survival, growth, biomass, and wood quality over multiple seasons. No agroecological recommendation for either region follows from the soil inventories alone.

LIMITATIONS, ECOLOGICAL RISKS, AND PERSISTENT MISCONCEPTIONS

Despite its demonstrated potential under optimized conditions, Paulownia cultivation is frequently accompanied by exaggerated expectations and oversimplified narratives. Many reported failures of Paulownia plantations can be traced not to inherent biological shortcomings, but to the misapplication of the species beyond its ecological and managerial limits. Addressing these limitations explicitly is essential for evidence-based deployment and for avoiding the reputational cycle of “promising introduction followed by widespread disappointment” that has characterized several fast-growing tree species.

Ecological risks and invasive potential

Among Paulownia species, ecological risk is highly unevenly distributed. *Paulownia tomentosa* has been repeatedly documented as invasive in parts of North America and Europe, where its prolific seed production, wind-mediated dispersal, and high germination capacity facilitate spontaneous colonization of disturbed habitats. Self-sustaining populations have been reported along transportation corridors, forest margins, and urban wastelands, raising concerns regarding competitive displacement of native vegetation and long-term ecosystem alteration. Invasive behavior of *P. tomentosa* is documented in some introduced regions, but the evidence for *P. elongata*, *P. fortunei*, and commercial hybrids is uneven. Limited reports of escapes do not demonstrate low risk. Clone-specific fertility, viable seed production, natural recruitment, disturbance, and regional climate should be

evaluated before introduction (Essl et al., 2007; Snow, 2015; Kadlec et al., 2026).

Misconception of universal adaptability

Claims of universal adaptability are inconsistent with the variation across reported field sites. Drought and salinity experiments show context-dependent growth reductions; they do not establish a common nonlinear response or a species-wide boundary between survival and productive biomass. A soil EC of 6–8 dS m⁻¹ has been mentioned as a possible productivity concern, but the underlying studies differ in genotype, plant age, exposure duration, and EC method. It should not be used here as a demonstrated threshold or converted from in vitro NaCl treatments. Site decisions require a defined EC protocol and measured growth response in local field trials.

Dependence on intensive management

Another common source of misinterpretation is the framing of Paulownia as a low-input or “set-and-forget” tree crop. Empirical evidence consistently contradicts this notion. High productivity in Paulownia systems is contingent upon precise irrigation scheduling, nutrient management, and stand design, particularly during the establishment phase. Deviations from optimal management – whether due to water scarcity, inadequate drainage, or insufficient fertilization – tend to produce disproportionately large yield penalties. This sensitivity does not imply unsuitability, but it does position Paulownia closer to intensively managed agricultural systems than to traditional forestry. Consequently, attempts to deploy Paulownia in marginal lands without adequate infrastructure often fail, reinforcing the false perception that the species itself is unreliable rather than misapplied.

Carbon and sustainability narratives – caution against overgeneralization

Carbon sequestration and sustainability claims associated with Paulownia further illustrate the risks of overgeneralization. While early-stage carbon uptake rates are undeniably high, these benefits are temporally concentrated and strongly influenced by harvest frequency and end-use pathways. Short-rotation systems oriented toward energy production recycle carbon rapidly back to the atmosphere, limiting long-term mitigation

potential unless biomass is directed into durable products. Moreover, ecosystem services such as soil improvement and erosion control are context-dependent and may diminish under intensive harvesting or suboptimal site conditions. Framing Paulownia as an inherently superior climate solution therefore obscures the conditional nature of its benefits and risks diverting attention from more robust, site-appropriate alternatives.

Toward realistic deployment frameworks

Taken together, these limitations suggest that Paulownia should be evaluated not as a universal solution, but as a high-performance, high-sensitivity system. Its strengths – rapid growth, favorable biomass chemistry, and compatibility with advanced biorefinery pathways – are best realized when ecological suitability, management capacity, and end-use objectives are carefully aligned. Conversely, ignoring these constraints increases the likelihood of ecological risk, economic loss, and policy backlash. Recognizing and communicating these boundaries is therefore not a weakness of Paulownia-based strategies, but a prerequisite for their credible and sustainable implementation.

CONCLUSIONS

This synthesis indicates that Paulownia plantation performance varies with identified genotype, site conditions, and management; direct field evidence is most informative for particular genotype–site combinations. Its main contribution is a framework that tests the link from site stress to measurable feedstock properties and then to product performance, while showing that most published studies examine only one or two links. Water limitation and salinity can reduce growth, but heterogeneous field and controlled studies do not establish a universal abrupt response, soil-EC threshold, or extrapolation from survival to economic yield. For salinity especially, exposure medium and EC protocol must be specified before comparing results.

Some selected hybrids perform well in managed trials, but their comparative growth stability, salt response, and reproductive risk cannot be ranked across sites without matched replicated tests. Genotype identity, local drainage and irrigation, and multi-season monitoring remain necessary. Paulownia wood has documented lightweight product applications; laboratory studies

also demonstrate possible fractionation, fermentation, and biochar routes. Cascading utilization is a promising hypothesis, but claims of superior efficiency or industrial value require feedstock-specific yields, comparative mass and energy balances, solvent recovery, scale-up, life-cycle assessment, and techno-economic analysis. No current synthesis demonstrates that drought- or salinity-grown Paulownia biomass has a process advantage.

Documented invasiveness of *P. tomentosa* in some regions requires regional risk assessment. Other species and hybrids cannot be presumed safe from the absence of escape reports. Azerbaijan soil and hydrological inventories identify candidate pilot sites, not confirmed Paulownia cultivation zones. Priority research consists of genotype-verified multi-site field trials with standardized salinity and water reporting, coupled to wood and process measurements on the same harvested material. Reproducible evidence screening, formal study-quality appraisal, clone-specific recruitment observations, and pilot economic and environmental assessments would allow firmer generalizations. Paulownia may contribute to selected wood products and prospective biorefinery value chains where verified planting stock and site management support reliable biomass supply. Its regional suitability, stress thresholds, hybrid advantages, and industrial comparisons remain conditional or untested; applications should therefore proceed through measured pilot trials and product-specific evaluation.

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