Review Article

Significance of Cultivating Genus *Paulownia* and its Utilization in Different Sectors: A Review

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Abstract | This review's objective is to determine the present level of knowledge about the origin and use of paulownia trees, especially in European countries where paulownia has just recently been introduced. Numerous studies on paulownia hybrids have demonstrated how the local environment and climatic circumstances significantly affect the growth value of individual clones. This difference is not only related to the development of the growth-related features, but also to the properties of the wood and the possibility of its utilization. Paulownia hybrids and cultivars have a similar appearance, but they react to their environment differently depending on the situation. The best growth (with good results) for this tree is in the Middle East and Southern Europe. These are regions where planting has been practiced extensively in the past. The cultivation of Paulownia today is usually achieved with hybrids of selected traits produced in vitro propagation. The major hybrids include in vitro clone 112, Cotevisa 2 and Shan Tong. Compared to Southern European countries, Central European countries have slower rates of growth and lesser manufacturing capacities. Paulownia breeding experiments are new and often replicate cultivation of Asian or Southern European hybrids. Agronomic techniques are, nevertheless, being produced, and studies are being conducted on responses to local variables. The benefits of growing paulownia in these areas and in other countries around the globe can be clearly seen in the years to come.

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Introduction

Due to rapid change in climatic conditions the need of research also gained speed in order to minimize the emission of CO_2. Bio mass could be used as the substitute means of energy to mitigate CO_2 emissions into the atmosphere. By 2050, Numerous forecasts have shown that there will be an ongoing increase in demand for wood and wood-based materials (López *et al*., 2012). There is a huge global trend to use fast growing woody trees for the purpose of biomass production (Testa *et al*., 2022). Paulownia is among the species of trees that grows the fastest, and in recent years, both academics and business have taken an interest in it. Various research projects have been conducted to determine

whether paulownia wood can be used as a raw material (Mohamad *et al*., 2021). Different research activities have been performed at the same time in different fields and the frequency of such practices is increasing by each month passed. On one hand these developments have a positive impact steering towards a wide analysis about the potentials of using paulownia, but on the other hand, various constraints are also being identified. Although the genus paulownia is native to China, it has rapidly spread throughout Asia, the USA, Australia, and Europe. (Chongpinitchai and Williams, 2021). Additionally, research on its cultivation has been done in central Africa (Essl, 2007). Over the past 20 years, there has been a significant interest in using paulownia wood for various purposes in European and Middle Eastern countries. The main goal of the current literature review was to determine the current state of research on the growing conditions and domains in which paulownia wood can be utilized.

Botany of paulownia

Paulownia a woody tree belongs to family Paulowniaceae (Kirkham and Fay, 2009). There is currently disagreement over how many species there are in Paulownia, with between six and twelve species recognized (Woods, 2008). The tree has been given the name paulownia in honor of Anna Pavlovna Romanova, the Grand Duchess of Russia who subsequently became the Dutch Queen (Christenhusz *et al*., 2017). The drooping crown of the paulownia tree resembles an umbrella, and the green sections of the plant are covered in small hair-like structures. The smooth, lenticelli-covered bark has a hue that ranges from greyish-brown to black. The enormous leaves that the sapling produces are between 15 and 30 cm long and 10 and 20 cm broad (Navroodi, 2013).

Propagation/Regeneration

Paulownias can be propagated via both vegetative reproductions as well as generatively; but in industrial settings, vegetative reproduction predominates. The earliest known technique of reproduction involved dividing roots, and it is also employed for different species (López *et al*., 2012). Mini-cuttings technique is another name for the root-splitting method used in the early stages of development (Temirov *et al*., 2021). But for many clones, the predominant mode of proliferation is the *in vitro* procedure (Testa *et al*., 2022). The process that is most important during the reproduction phase is the establishment of a strong, well-established root system (Filipova *et al*., 2019).

Figure 1: *The inflorescence in Paulownia tomentosa (Costea et al., 2021).*

Hybrids

The most common species grown are *Paulownia tomentosa* (Figure 1), *Paulownia elongata, Paulownia fortunei, Paulownia taiwaniana, Paulownia fargesii, Paulownia galbrata* and *Paulownia catalpifolia* (Jensen, 2016). Pure botanical species were employed in the past when paulownias were distributed over the globe. One of the first nations to do so extensively was the USA, which imported paulownia species around 1840. Paulownia has been referred to as the tree of the future due to its rapid growth rate. It has spread over several states over the past 150 years and has created a number of problems as a result, sparking a fierce discussion about all paulownia species. Officially designated as an invasive plant, *P. tomentosa* has been eradicated from numerous states. *P.elongata*, on the other hand, is not often regarded as an invasive species but is nonetheless resistant to acceptance (Snow, 2015). According to recent research, *P. tomentosa* can proliferate in areas where stands have been devastated by numerous disasters and disturbances, especially in the canopy (Chongpinitchai and Williams, 2021). Some nations have designated specific paulownia species as dangerous, such as Austria, which has classified *P. tomentosa* as a species that is invasive (Essl, 2007). Additionally, the Czech Republic has observed and assessed it as an extraterrestrial species under regular check and balance (Pergl *et al*., 2016).

The Polish Government has also taken precautions to reduce the widespread paulownia infestation (Jakubowski *et al*., 2018). In Asia, natural species of paulownia are still cultivated, all the way to Turkey, but hybrids are quickly replacing them. Hybrids have only achieved significance as a fruitful product in some countries like Bulgaria, where prior cultivation of species had been failed (Gyuleva, 2008). Individuals from several well-known species, like *P. elongate* × *P. fortunei*, which exhibit greater fruitfulness and excellent environmental adaptability, are chosen for the generation of hybrids (San *et al*., 2016) and *P. fortunei* × *P. tomentosa* (Ayan *et al*., 2006). Clones made *in vitro* are among the top hybrids (Kadlec *et al*., 2021). Cotevisa 2, Sundsu 11 (Zuazo *et al*., 2013) and Shan Tong (Figure 2) (Sedlar *et al*., 2020). Arctic is one example of an unfamiliar mix (Jensen, 2016) and the selected genotypes PWCOT-2, PW-105, PWL-1, PWST-33 and PWST-11 (Olave *et al*., 2015). Additionally, naturally occurring hybrids like *P. taiwaniana* exist which was produced by crossing *P. fortunei* with *P. kawakamii* (Costea *et al*., 2021). On occasion, rarer hybrids like the 9501 (*P. fortunei* × *P. elongate*) (*P. fortune* × *P. tomentosa*) are discovered (Sedlar *et al*., 2020). Depending on the intended function, plantations of paulownia are grown at a particular density. They are often planted with a 2 × 1.5 m^2 to 4 × 4 m^2 spacing. Approximately 2000–3300 plants/ha are planted for the production of biomass, compared to only 550–750 trees/ha for the production of lumber. Hybrid paulownias are grown in brief cycles lasting six to ten years for round wood production, but these cycles can be even shorter for biomass production (Berdón *et al*., 2017).

Figure 2: *Paulownia Shan tong (tomentosa × fortunei) year 1 in nursery (Costea et al., 2021).*

They demonstrate a wide range of biological actions, including antioxidant, anti-inflammatory, antibacterial, antiviral, neuroprotective, antiproliferative, anti-cancer, cytotoxic, and anti-hyperlipidemic activities (Molčanová *et al*., 2021) as shown in Figure 3 (Sławińska *et al*., 2023).

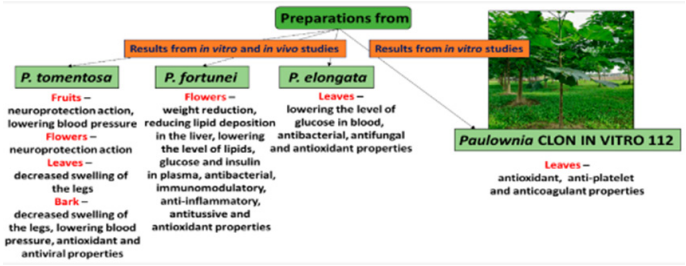

Figure 3: *Biological activity of preparations from organs of various species of Paulownia (Sławińska et al., 2023).*

Paulownia's phenolic compounds have antioxidant qualities, making them useful for the pharmaceutical sector (Barbu *et al*., 2023a).

Growth conditions

The ability of paulownia to grow to large sizes in a very short amount of time is perhaps its most well-known characteristic; in China, it has been said that paulownia looks like a pole in one year, an umbrella in three years, and can be cut into boards in five years (García-Morote *et al*., 2014). The 80-years old *P. fortunei* growing in Kweichow Province reached a height of 49.5 m, a diameter at breast height (DBH) of 202 cm, and a wood volume of 34 m^3, while another specimen, at 90 years of age, had a 224 cm DBH and 44 m^3 of wood volume. There have also been reports of record-breaking specimens from China. A *P. fortunei* tree that was 11 years old and was grown in the Guangxi Zhuang Autonomous Region in southern China was 22 meters tall, had a DBH of 75.1 cm, and had a wood volume of 3.69 m^3 among the young trees. *P. elongata* has also grown to similar sizes (García-Morote *et al*., 2014). Paulownias in China normally achieve a 30-40 cm DBH in 10 years and yield about 0.3-0.5 m^3 of wood, while under the right circumstances, beneficial wood can be produced in 5–6 years (García-Morote *et al*., 2014). In China and Southeast Asia, the practice of growing wild species as crops has long been widespread. Even though it is placed next to the rapidly expanding poplar, the paulownia established itself solidly in terms of growth dynamics (Navroodi, 2013). In contrast to other fast-growing trees like willow, poplar, eucalyptus, and red oak, paulownia has achieved outstanding growth

under favorable growth conditions, according to numerous researches (Janji´c and Janji´c, 2019).

Paulownias have huge leaves while they are young, and because the stem is not yet sufficiently woody, it is susceptible to mechanical harm. Strong winds are another potentially detrimental aspect because they have the potential to completely destroy a plantation in open areas (Jakubowski and Dobroczy´nski, 2020). Considerable study has been done to address the issue of the creation of a strong and well-developed root system, which is a crucial component of the reproduction phase (Mohamad *et al*., 2022). Studies conducted in New Zealand have shown that winds as little as 40 km/h can harm young trees and branches, and that even in its third or fourth year, a tree's growth can still be restricted by the wind (Barton *et al*., 2007). In the first four to six years following planting, paulownia shows a high intensity of increase and with age, their rate of growth slows down (Costea *et al*., 2021) (See Table 1 given below).

Only a few hybrids have been allowed into widespread cultivation because pure species, including *P. tomentosa* and even *P. fortunei*, have been proven to be invasive through experience. Given the geographies involved, southern Europe specifically, Spain, Portugal, Italy, and the Balkans as well as Middle Eastern nations like Turkey and Iran, where conditions are likewise significantly better than in countries further north, are the ideal places for the cultivation of paulownia hybrids. Though geographically it varies a lot but the amount of positive encounters points towards a tremendous potential (Tusevhaan *et al*., 2023). Moreover, for *P. elongata*, mass propagation of this species appears to be promising when utilizing softwood shoot forcing followed by root induction. Additionally, by using this technique, plant material that is somewhat cleaner and appropriate, explants can be obtained for use in a variety of in vitro research applications (Maqbool and Aftab, 2024).

Diseases

Likewise other plants, paulownia can also catch pathogenic diseases. Witches broom is the most popular disease in paulownia, a circumstance that has long been noted in China (Jakubowski *et al*., 2018). Modern experiments have found that phytoplasma (a parasite) responsible of witches' broom, which can be contagious between paulownia trees (Gao *et al*., 2008). Recent investigations conducted in Poland have revealed the presence of nematodes (Meloidogyne hapla) in *P. tomentosa* roots (Skwiercz *et al*., 2020).

Qualities and applications of paulownia wood

Wood structure

Paulownia's heartwood ranges in color from light yellow to bright crimson. Heartwood and sapwood do not clearly separate from one another. One- or two-yearly rings are typically present in the sapwood, which is quite thin. Every cross-section clearly reveals annual rings. The structure of the wood is ring-porous or semi-ring-porous. The tree rays can only be seen with magnification because the vessels are either barely or completely invisible (García-Morote *et al*., 2014).

Customary applications for paulownia wood

The usage of paulownia wood was originally documented several centuries before the present (BCE) (Nagata *et al*., 2013). Due to its association with birth and death and use in both religion and medicine, the tree was revered and used extensively. The tree has been the subject of numerous myths, mostly in China and Japan. Since the third century CE, paulownia has been widely farmed (García-Morote *et al*., 2014). Paulownia wood is widely utilized today due to its popularity and ability to thrive in a variety of environments.

Table 1: *Comparative study on the growth rate of the paulownia genus compared to other genera used for wood biomass.*

Genus	Height annual growth (m) in the first 5 years	Plant size after 3 years (m)	Maximum height at maturity (m)	Diameter of the trunk annual growth rate (cm)
Paulownia spp.	3-6	10.0 – 17.5	15-30	1- 2.5
Populus nigra/deltoides	2-3.5	9-12	20-25/20-30	1-2
Salix spp. Hybrid/*Babylonica*	1.5-4/1.5-2.5	7-12/4.5-9	15-25/15-20	1-1.5
Quercus spp.	2.5-3	7.5-10	10-20	1.5-2
Eucalyptus	2-2.5	6-9	10-15	1-1.5

Processed after JANJIĆ and JANJIĆ 2019 (Costea et al., 2021)

Plywood, paper, veneers, hand carvings, clogs, engineered wood (apart from construction wood), and furniture and kitchenware like rice cookers, water buckets, bowls, spoons, and sticks are all made from paulownia wood. Music instruments are frequently made from paulownia wood (Latib *et al*., 2020). Tests contrasting the wood of paulownia (*P. elongata)* with that of poplar (*Populus tremula*) and juniper (*Juniperus excelsa*), which are commonly utilized in these goods and have demonstrated excellent assurance in terms of wood characteristics, positive results have been achieved for the practical use in the manufacture of pencils and crayons (Kaygin *et al*., 2015). Paulownia flowers, leaves, and their remnants can be used for medical purposes in addition to the wood's applications (Nowak *et al*., 2022).

Pulp industry

Years ago, the US suggested using *P. tomentosa* in the pulp business; however, because paulownia has short fibers, researchers have emphasized that it is only appropriate for specific grades of paper (Koman *et al*., 2017). Paulownia is helpful for the pulp industry because of its high cellulose content (47.85%), according to Popovic and Radosevic (Popovi´c and Radoševi´c, 2011). Paulownia wood has a short production cycle, so it is possible to use both the trunk and the branches simultaneously. The latter has a lower value and is frequently combined with reaction wood, but it is still useful for making paper, nanocellulose, charcoal, and other products (Qi *et al*., 2016).

Energy targets and other benefits

Paulownia plantings focused on biomass generation are growing in popularity right now (Magar *et al*., 2018). The biomass that a paulownia tree can produce in a year is comparable to what other species can produce in a few years (Zuazo *et al*., 2013). Paulownia performs poorly at creating efficient fuel due to its quick growth rate and low wood density. According to European standards, a comparison of *P. elongata* × *P. fortunei* pellets from young plantations revealed that they were of inferior quality than those made from *Pinus radiata* and *Eucalyptus nitens* (Pegoretti Leite de Souza *et al*., 2021). In a distinct investigation, *P.tomentosa* and *P.elongate* showed the proper findings while assessing the production of briquettes and pellets from sawdust (Spirchez *et al*., 2021). Paulownia wood is currently the subject of extensive study to support its use in the creation of biopolymers (Rodríguez-Seoane *et al*., 2020) as well as wood plastics and composites (Ebrahimi *et al*., 2021). Paulownia wood also works well as a component in the manufacture of lightweight particleboards (Nelis and Mai., 2021) and block boards, which serve as a core layer in between veneers (Nelis *et al*., 2019). The plant's leftover components, including its leaves and blossoms, can be used for medical purposes (Yang *et al*., 2019) and as a source of food for animals (Huang *et al*., 2021). Paulownia Solid Wood Panels (SWPs) are lightweight, sustainable core materials that can be utilized in non-load-bearing constructions, sporting goods, and sandwich structures for the furniture and packaging industries (Barbu *et al*., 2023b).

Paulownia Species in Context to Climate Change Mitigation

The ability of paulownia trees to absorb CO_2 from the atmosphere has also drawn interest. These trees are exceptional for their remarkable capacities to sequester carbon dioxide, and they grow quickly as well. Their ability to absorb significant amounts of CO_2 when cultivated in sufficient quantities makes them a possible answer for mitigating the effects of climate change (Janjić and Janjić, 2019). Due to their reputation for air-purifying qualities, they are also regarded as one of the most promising C4 trees (Testa *et al*., 2022). Despite having different characteristics and habitats, terrestrial C4 plants like paulownia trees are photosynthetic nature with a higher capacity for biological CO_2 fixation than other aquatic and terrestrial plants (Mansour *et al*., 2022). *P. tomentosa*, a commercial woody plant with rapid growth, can be interplanted in an agroforestry system to assist reduce greenhouse gas emissions. To determine a realistic estimate of *P. tomentosa's* total carbon biomass, more forest trial study is required (Magar *et al*., 2018).

Conclusions and Recommendations

According to the information discussed in this article, paulownia planting in a short cycle is mostly done to produce wood biomass for use in energy production as well as other industries like pulp and wood processing and mixed wood production. Other plant parts, like the leaves and flowers, have been researched for animal feed and medicine to a lesser extent. Wherever paulownia species are found and where paulownia trees reach their full size, that is where wood is used to make furniture and generally for machining. Only

a few hybrids have been successfully produced for large-scale production since information suggests that invasive paulownia trees include *P. tomentosa* and even *P. fortunei*. Moreover, paulownia species can also play an important role in climate change mitigation and carbon sequestration process by reducing the level of greenhouse gas emissions and purifying air quality, adding more significance to its cultivation. The best locations for growing paulownia hybrids, geographically speaking, are in Southern Europe, particularly in Spain, Portugal, Italy, and the Balkans, as well as the Middle East, which has many advantages over northern countries like Turkey and Iran. Although it differs from region to region, the quantity of positive encounters indicates good potential. Between species and hybrids, there are differences in reported quality characteristics, chemical makeup, growing conditions, and biomass production. Published research findings can vary, sometimes by as much as 10% or more. The effectiveness of the chosen strain or hybrid for each experiment should be determined. Due to paulownia's late arrival in Central and Eastern Europe, experiments there are still in their early stages. But compared to Southern Europe, there are already symptoms of low output. This conclusion is the result of a number of variables, chief among which is the brief growing season, which inhibits seed growth and biomass output. Second, there is a lot of frost and low temperatures in the spring and autumn seasons. This does not preclude the notion of introducing paulownia to this part of Europe, but more research is needed to establish the culture strategy that would best fit the paulownia tree to a particular environment.

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Novelty Statement

This review presents a comprehensive overview of Paulownia growth, challenging outdated perceptions of its adaptability and resilience. Additionally, it provides the journal's audience with valuable insights into recent developments in Paulownia research, addressing gaps in understanding its economic potential and applications across multiple sectors globally, under diverse land uses and ecological zones.

Author's Contribution

Asim Karim: Principal author, Writing - Original draft and visualization.
Anwar Ali: Supervision.
Bilal Ahmed Qazi: Helping manuscript writing.
Nowsherwan Zarif: Critical review
Wadood Shah: Critical analysis, review and editing manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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