GENUS *PAULOWNIA*: VERSATILE WOODSPECIES WITH MULTIPLE USES - A REVIEW

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Abstract. *Short-rotation plantations for wood biomass production are systems in which different, fast-growing forest species are grown in intensive agricultural technologies to achieve high biomass yields. The genus paulownia comprises very fast-growing tree species, mainly used in biomass production for energy purposes, but not only. The biomass produced by this plant is used in its entirety; as heating material, industrial, ecological and decorative wood, protection of soil erosion, phytoremediation of polluted soils, air purification, animal feed, pharmaceutical industry, melifer, etc. Among the most promising applications are the production of biopolymers and bioethanol derived from cellulose. The proper cultivation and use of paulownia species contribute to maintaining ecological balance and nature conservation. The main objective of the paper was to carry out a careful and detailed analysis of the specific scientific literature describing their main characteristics and practical applicability to the different species of the genus Paulownia. The paper also examines the importance of cultivating paulownia species under conditions of economic viability while ensuring the maintenance of biodiversity and the protection of ecosystems.*

Keywords*: multipurpose specie; biomass production; fast growth; environmental requirements; cultivation technology;*

INTRODUCTION

Paulownia is a deciduous tree capable of reaching very high growth rates in favorable climatic conditions and advanced technology. The genus *Paulownia* (*Scrophulariaceae*) includes nine species of fast-growing trees native to China and East Asia (ZHU et al., 1986). These species have also been introduced to North America, Australia, Europe and Japan. Paulownia could be considered a plant with low moisture claims, even if the growth rate is very slow in dry areas (CAPARROS et al., 2008). *Paulownia tomentosa* Steud. (*Scrophulariaceae*) is an ornamental tree widely found in China, Korea and Japan. The special characteristics of this species manifested by wood tolerance to rot, dimensional stability and a very high flash point ensure the popularity of this type of woody mass on the world market (BERGMANN, 1998; SILVESTRE et al., 2005).

Thus, paulownia is a fast-growing hardwood tree (from *the Paulowniaceae* family, formerly *Scrophulariaceae)* consisting of nine species and several natural hybrids, native to China (FREEMAN, 2012). The most important species of the genus are represented by; *P. elongata, P. tomentosa*, *P. fortunei*, *P. fargersii albiphloea*, *P. kawakamii, P. catalpifolia* and *P. australis* (ZHU, 1986). These species of paulownia grow in nature and cultivated in different regions of the world from China, Asia of Southeast, Japan and Australia to North and Central America and Europe. Paulownia genus species are well adapted for a large variation of the economic and climatic factors growing well on marginal and erodated lands, with low productive potential for other species of agricultural or forestry interest. Paulownia plants grow at different altitudes, from the plains up to 2000 meters (ZHU, 1986).

Most species of paulownia have as their genetic origin center in China, being used for various purposes for over 2600 years. The genus name was attributed in honour of Queen Anna Pavlovna of the Netherlands (1795-1865) by a german botanist who was helped by the queen to finance her expedition to Southeast Asia (WOODS, 2008). Following the expedition, the book "Flora Japonica" was published in which the various species of paulownia are detailed described, and the multiple attributes and uses of the trees are also presented. The name paulownia was then accepted and appreciated by the Japanese.

Research carried out by ZHAO-HUA et al., (1986) attests to the existence of nine important species of the genus Paulownia, all of which originated in the genetic center of East Asia. The various species of paulownia, but especially *P. tomentosa*, have been cultivated as ornamental plants in Europe since the beginning of the 19 th century, but their commercial value has only been discovered in recent decades.

The genus Paulownia is unique in the plant kingdom due to the rapid rate of accumulation of wood biomass and multiple areas of use, with historical documents attesting to its use as early as 2600 BC

The research results carried out by JENSEN (2016) show that the interspecific species and hybrids of paulownia could successfully represent an agro-forestry commercial culture in north-west, central and south-

eastern Europe. The multiplication of paulownia species can be relatively simply done by roots and stem cutting, seeds and "in vitro" techniques. Commercial hibrids of paulownia obtained through intra and inter-specific cross breeding strips exhibit a high yield of biomass accumulation, superior qualities of wood mass and tolerance to biotic and abiotic stressors, which can be purchased from different nurseries around the world. WENHUA (2001) noted that interspecific hybrids with excellent attributes were obtained; *Paulownia fortunei x Paulownia tomentosa* which offers a higher volume of wood by up to 30% compared to *Paulownia elongata* and arealso suitable in intercropping technologies.

In recent years, there has been an enormous increase in demand for biomass raw materials for renewable energy production, due to the obligation to reduce the role of fossil fuels and the related environmental impact (WELFLE et al., 2020). Romania, together with other European countries, is trying to reduce the consumption of fossil fuels in order to reduce environmental pollution, including through land afforestation programmes by cultivating species and interspecific hybrids of paulownia.

Pulownia trees have multipurpose uses, so the objectives of setting up a plantation are not only linked by the production of wood biomass, but also the regeneration of degraded soils, the use of manure or the production of pulp wood for paper (OLSON and CARPENTER, 1985). Paulownia is a suitable tree for intensive management in short-rotation hardwood plantations, due to its rapid growth, ability to regenerate from the stump and the multiple varieties through which the wood and its fibres can be used. After harvesting paulownia should not be replanted because it regenerates by starting in vegetation the buds on the stumps. The paulownia wood has several quality attributes such as; moisture resistance, rigidity, pleasant colour, good resonance, reduced mass, rapid drying, etc., which increases its value (CLATTERBUCK and HODGES, 2004).

The widespread use of paulownia wood in the construction sector has occurred mainly due to successive price increases in balsa wood *(Ochroma pyramidale*) which was used in sandwich structures in the construction of automotive, ships, aircraft or wind energy (LI et al., 2010).

Studs carried out over time have demonstrated the value of this species by showing that an 8-10 year old paulownia plant can produce 100 kg of fresh leaves per year with a high nutritional value for ruminants, pigs and rabbits (BODNÁR et al., 2014; WANG and SHOGREN, 1992; ZHAO-HUA et al, 1986), which can serve as natural soil fertilizers due to high nitrogen, phosphorus and potassium content (WANG and SHOGREN, 1992).

Therefore, the carried out researches has shown that paulownia is an extremely versatile plant, which has attracted particular interest due to various properties such as; high resistance against adverse pedo-climatic conditions (Chinese Academy of Forestry, 1986); rapid growth rate as well as high yield in short rotation (AYRILMIS and KAYMAKCI, 2013); a substantial fibre content for paper production (ASHORI and NOURBAKHSH, 2009); beneficial uses for medicinal purposes, (healing bronchitis, lowering cough and controlling high blood pressure) (Chinese Academy of Forestry, 1986); sequestration of high carbon emissions (BASU et al., 2016) and, most importantly, great energy potential. Thus, paulownia is recognised as a promising renewable raw material for the production of biofuels. In this regard, a critical question arises as to how to find suitable locations for the cultivation of the plant.

MATERIAL AND METHODS

The research was mainly based on the theoretical analysis of the bibliographic sources existing in the mainstream of publications being accompanied by the experiences and results of own research. The existing theoretical and practical knowledge of the literature and its role in designing viable business models specific to this subject were analysed.

RESULTS AND DISCUSSIONS

General description of paulownia plant

Paulownia genus is part of the *Paulowniaceae* family and have over 20 plant species (20-25 species according to different authors) with similar attributes and uses given the general name of paulownia. The species identified so far are; *Paulownia tomentosa, P. elongata, P. fortunei, P. australis, P. catalpifolia, P. fargersii, P. silvestris, P. coreana, P. duducoxii, P. wealth, P. albiphloea, P. glabra, P. grandifolia, P. imperialis, P. kawakamii, P. lilacina, P. longifolia, P. meridionalis, P. mikado, P. recurva, P. rehderiana, P. sinesis, P. taiwaniana, P. thyrsoidea, P. viscosae.*

Paulownia is a C_4 photosynthetic type woody tree with large, pubescent leaves (fig.1) of about 60-70 cm diam. and flowers of different colors from white to intense purple, with strong and pleasant smell, with the diameter of the corolla of 4-6 cm. Depending on the environmental conditions and the applied technology, the trees can reach up to 30 meters high, with a trunk 1 m diameter. Soil requirements are moderate, increases on any soil type, even on dry soils with alkaline reaction. However, the best growth rates will be achieved on deep soils, with medium moisture levels, drained and aerate, generally clay soils with high levels of fertility. Paulownia is a heliophile species and therefore prefers open and sunny areas.

Figure 1. Paulownia Shan tong (*tomentosa x fortunei*) year 1 in nursery (original)

Root system

Paulownia is a tree with a deep root system that explores a huge volume of soil. The roots of the surface layer of the soil are thin, strongly branched, forming a dense network. Absorption roots have a diameter of about 1-7 mm and can extend up to 70-90 cm. The growth and dispersion in the soil of the root system is significantly influenced by the level of groundwater, the physico-chemical characteristics of the soil. Paulownia is best suited for easy mechanical soil composition with good drainage.

The deep distribution of the roots of a mature paulownia tree can reach up to 30 m, with a diameter of about 28 m, i.e. about 3 times larger than the canopy. Around 70-80% of the roots with absorption role are located on the depth of 40-100 cm in the soil profile.

Trunk and bark

In general, paulownia species can be grown in a monoax system, i.e. on a single trunk, in which case work is carried out to elag the stem over a length of 4,5 m from the base, or on multiple stems, usually after the first two harvest cycles. The diameter of the trunk of a tree of 1.5-2 years is generally between 7 and 14 cm, a 3-4 year old specimen is 20-30 cm, and an mature tree of 15 years is up to 60 cm.

The bark is thin, light gray, smooth, slightly cracked in mature specimens.

The foliar apparatus

In the first year, paulownia saplings present a large, pubescent leaves, 40-80 cm in diameter (fig.1). The leaves are cordiform or ovated with round edges, of intense green color due to the high content of assimilating pigments, with the lamina structure specific to plants of type photosynthetic C_4 characterized by the presence of perivascular sheath cells as essential elements of photosynthesis. The color of the leaves does not change in autumn. The leaves fall when they're green, then they dry out.

The flower

The flowers are large, blue-violet, lilac or almost white and are grouped in large apical panics with strong fragrance (figure 2). Paulownia species exhibit alternating flowering and fruiting, with seasons that manifest themselves through flowering and abundant fruiting and others with few flowers. Species of paulownia

of ornamental interest have a greater capacity to produce flowers compared to those of economic interest or with interspecific hybrids

Late spring (April-May) takes place in the flowering period and lasts 4-6 weeks, making this tree an ideal material for greening cities and promenade areas.

Figure 2. The inflorescence in *Paulownia tomentosa* (original)

The fruits and seeds

Fruits are long, lignified and rigid capsules with dimensions between 10 and 30 mm. The seeds are small, light, butterfly-shaped, 2 to 5 mm long, membranes, fitted with bractes (figure 3).

Paulownia produces numerous fine seeds with wings (up to 2000 seeds per fruit), one gram containing about 5000 seeds (JIMENEZ et al., 2005). Scanning seeds through electronic microscopy show the existence of an extended network of fine tubes that can play an important role in maintaining the structural integrity of the wing to help disperse with wind and to create water access channels to stimulate germination. Studies on the development of seedlings after germination show that a photoperiod of 16 hours is optimal for leaf generation, growth of stems and roots and total accumulation of dry mass (CARPENTER et al. 1983).

The seeds germinate in optimal conditions in less than 7 days, and the appearance of the first true leaves occurs about two weeks after germination. Paulownia seeds are rich in lipids represented by palmitic acid (approximately 7 %), oleic (approx. 20 %) and linoleic (approximately 65 %), γ-tocopherol (approx. 10.0 %). The seeds also contain about 10 % protein, 9 % cellulose and 40 % soluble sugars (ANGELOVA et al., 2011).

Figure 3. Paulownia tomentosa seeds and fruit section (original)

Growth rate:

The high intensity of increases in paulownia is recorded in the first 4-6 years after planting and receiving, and with age the rate of growth is reduced

Table 1

Comparative study on the growth rate of the paulownia genus compared to other genera used for wood biomass production

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
Eucaliptus	2-2.5	6-9	10-15	1-1,5

- Processed after JANJIĆ and JANJIĆ 2019.

THE ECONOMIC IMPORTANCE

Paulownia presents as I pointed out a series of attributes related to water wood resistance, dimensional stability and high flash point (LI and ODA, 2007), attributes that ensure the popularity of its wood on the world market (BERGMANN and WHETTEN 1998; EL SOUWK and EL SOUWK 2003). For centuries, Japanese craftsmen have used it as revered wood in ceremonial furniture, musical instruments, decorative moldings, laminated structural beams and shipping containers. This species was introduced to the United States in the mid-1800s in the form of seeds, used as a material associated with porcelain packaging. Once unpacked, small and light seeds were dispersed by the wind and naturalized in all eastern American states. The cultivation of paulownia species for wood mass production is not yet very well organized but tends to become increasingly important both on the North American continent and in other areas, especially due to the high demand on the market.

Paulownia as multifunctional tree

Under natural conditions, a 10-year-old paulownia tree measures 30 to 40 cm in diameter at 1.30 m and contains a wood volume of 0.3 to 0.5 m^3 (ZHU et al., 1986). The wood of paulovnia is light but hard, dries quite quickly and has a pleasant aesthetic appearance of light color like grain seeds, does not deform and does not break easily. In addition, wood is easy to process, suitable for carving and has excellent insulation properties (ZHU et al., 1986). Several species have been planted extensively in Australia to meet the demand for wood (BEEL et al., 2005). Due to the rapid growth and high cellulose content (440 g. cellulose/kg), studies have been carried out to determine whether it is suitable for the cellulose and solid biofuel and cellulose industries (LOPEZ et al., 2012).

The thin branches of paulownia are successfully used to create biodegradable lignocellulosic biocomposite with Poly Lactic Acid (PLA), thus introducing a new product on the market (TISSERAT, 2013). A recent study showed that *P. elongata* wood flour could be used in the production of stuffed polypropylene composites (TISSERAT et al., 2013). Paulownia flowers and leaves are a good source of lipids, carbohydrates and proteins, and used as feed for pigs, sheep and rabbits (ZHU et al., 1986). The high nitrogen content of paulownia leaves can be compared to that of a leguminous, therefore they can be used as green fertilizer. Due to the active principles contained by different organs of paulownia plants they are used in the treatment of diseases by traditional chinese medicine (ZHU, 1986). Paulownia blooms are large size and represent good melifer source (ZHU, 1986). Paulownia was capitalised for agro-forestry (KAYMAKCI and AYRILMIS 2013, WANG and SOGREN, 1992), biomass production (RIANG et al., 1994), degraded and polluted land improvement (SONG 1988) and animal waste remediation (CARPENTER, 1977).

Biomas production

Recent research has shown that the resources of wood biomass are large enough to cover a substantial part of the world's primary energy consumption in 2050. However, these resources have multiple uses and their accessibility is limited, which tends to decrease their competitiveness compared to other forms of energy (LAURI et al.2014; MADEJÓN et al., 2016).

In the southeastern United States of America there were over 12 million hectares of forest, grassland and degraded land. Much of this land could potentially be used to be cultivated with valuable tree species

paulownia being one of these species (BERGMANN et al., 1977). Due to rapid growth and valuable attributes, its potential as a basic crop for biofuel has been detailed studied (CLATERRBUCK and HODGES 2004, JOWEE 2012). A major advantage of using biomass as a source of fuels or chemicals is its rapid renewal. Wood from modified forest trees for high cellulose and hemicellulose production could be an important raw material for the production of bioethanol. In a biomass comparison study conducted in Germany, *P. tomentosa* (12.7 tonnes/ha) produced more than *Salix viminalis* (8.2 tonnes/ha) on a short rotation asolament under non-irrigated conditions (MAYER, 2004).

An assessment of the qualities of paulownia wood showed a composition in 14.0% extractive substances, 50.55% cellulose, 21.36% lignin, 0.49% ash, 13.6% hemicellulose (JOWEEE 2012). Ongoing research at Fort Valley State University (FVSU) has established that the biomass harvested by *Paulownia elongata* after 30 months (after three growing seasons) is nearly 92 kg/tree (unpublished results). Under favourable conditions, an intensive plantation of 2000 plants per ha can produce up to 150 to 300 tonnes of wood annually, only 5 to 7 years after planting (JIMENEZ et al., 2005). However, further studies are needed to demonstrate the potential of biomass in different soil and climate types.

Main aspects of cultivation technology

Influence of environmental factors on growth and development in *Paulownia sp.*

Temperature requirements

Paulownia plants tolerate a fairly wide range of temperatures with a minimum limit of around -25 ºC and a maximum of about 47 ºC. The optimum temperature is 25-27 ºC. Within the genus, *Paulownia elongata* resists low temperatures up to -25 ºC, *P. tomentosa* to -20 ºC while *P. fortunei* -15 ºC. All species are susceptible to late spring frost after starting in vegetation affecting vegetative and florifers buds.

Soil requirements

Plants of *Paulownia sp.are* not pretentious to the edafic factor and can provide good results on sandy and clay soils as well as heavy soils. However, there are some differences in the clay content of the soil, its pH and the groundwater level. The clay content of the soils on which different species of paulownia grow varies greatly. Arctic paulownia and paulownia *Shang Tong* (hybrid intersepcific between *P. tomentosa and P. fortunei)* grow well onsoils characterized by a clay content ranging from 16.25% to 23.49%, while plants belonging to other species of the genus vegetate on soils characterized by a clay content of less than 10% (Chinese Academy, 1999).

Most of the species of paulownia exhibit a deep and strongly branched root system. The growth and expansion of the root system requires not only adequate water and temperature conditions, but also well-ventilated soils. *Paulownia sp*. requires a total soil porosity of more than 50%. As regards soils containing excess clay, the species with the best behaviour under these conditions are *Paulownia fortunei* and *Paulownia tomentosa* (RADU et al., 1977). Paulownia trees are sensitive to both groundwater depth and soil salinity. In general, the depth of groundwater should not be above 1.5 meters, a period of water stagnation greater than 3-4 days may prove lethal for plants.

Soil salinity of more than 1% significantly affects plant growth. Soil pH value and salinity tolerance vary by species, as follows; *Paulownia elongata and Paulownia tomentosa* vegetate well on soils with pH between 5.0 and 8.9 and *Paulownia fargesii, Paulownia albiphloea* on soils with pH between 5.6 and 6.0. Plants of the species *P. fortunei* can reach an average growth threshold in diameter of 3.6 centimeters and 4.2 centimeters on slightly acidic soils, and also on soils with a pH content of more than 8.0, and *P. elongata* and tomentosa show good growth on an even greater variety of soils. Paulownia trees can take selectively the ions of calcium and magnesium from the soil.

Fertilizer requirements

Soil analyses are intended to provide certainty about the level of soil supply of nutrients, at least with the main macronutrients; nitrogen, phosphorus, potassium calcium and magnesium, as well as the current pH value. If the first imbalances are already recorded, they must be remedied by appropriate fertilisation measures. During the growth of paulownia plants attention should be paid to an appropriate supply of nitrogen and potassium, with particular attention to potassium containing fertilisers wich may contain chlorine, as they may induce negative effects on plants. Especially in the first years the plants need many nutrients and in high quantities to be able to develop properly. This leads to the need to optimize plant nutrition.

Moisture requirements

In general, paulownia plants grow under conditions with a minimum annual rainfall of 500 mm and a maximum of 3000 mm. The distribution of precipitation is also important, some studies mention that *Paulownia sp.* normally develops in the context that 65% of annual rainfall falls during the period of intense plant growth (June-August for Romania). Paulownia requires regular watering only for the first two years. Water consumption on a brood is 30-40 l 1-2 times a week. After the development of the root system (third year), the needs for special watering are reduced.

The most drought-tolerant species are *P. tomentosa*, followed by a reduction in tolerance to *P. elongata, P. kawakami, P. fortunei* and *P. catalpifolia.* The water excess of soils is also dangerous, tests carried out in the Danube Delta by RADU et al. (1977) indicate that saplings grown on land characterized by excessive soil moisture until June-July have completely disappeared from the first year.

Light requirements

Paulownia is a light-loving tree. Studies on species of *P. elongata* and *P. taiwanese* showed that the point of saturation to light is 60,000 lux (60% of the light of a clear day), while for most other tree species the saturation point is around 20,000-30,000 lux (20-30% of total sunlight). *P. fortunei* and *P. fargesii* have the highest tolerance to shading. In general, the plants of the genus *Paulownia* produce distinct dispersed branches and leaves, allowing the passage of light. A slight difference in light intensity on one lateral side may cause distortion of the shape of the shaft canopy. According to experiments carried out on *Paulownia sp.* saplings, a reduction of 30 % in light intensity can seriously affect plants, which confirms the preference of this species for intense light. Therefore, intercropping cultivation with other fast-growing trees and the presence of taller specimens nearby are not recommended.

Influence of strong winds and snow

Strong winds can cause total or partial destruction of saplings and young trees, while it does not appear to affect mature trees. At wind speeds of more than 40 km/h, shoots and branches can be broken. However, in any case, it is not recommended to plant paulownia in areas with strong winds with speeds of more than 30-40 km/h. Also, large amounts of snow falling in a short period of time can cause thinner branches to break.

Pests and pollution.

Paulownia wood accumulates tannin which makes it tolerant to the attack of harmful insects. Paulownia feels good in urban conditions, with air and soil pollution conditions. Due to the high ecological plasticity this plant can be successfully grown on both heavy metal-polluted and low-fertility soils unsuitable for other crops.

Regeneration of a tree

The uniqueness of paulownia lies in the fact that after exploitation the tree does not need re-planting. After each cut, the tree regenerates from the vegetative buds located at the base of stems. The life of the root system is 70-100 years and can be used efficiently between 4 and 9 cycles of eight years, which offers the possibility to resume the production process without new planting costs. The trunk can be cut at any time of the year, despite the season and short harvesting periods, which is not the case with other tree species.

CONCLUSIONS

Paulownia is a hardwood fast growing tree (the *Paulowniaceae* family) consisting of over 20 species and a few natural hybrids.

The most important species of the genus include; *P. albiphloea, P. australis, P. catalpifolia, P. elongata, P. fargesii, P. fortunei, P. kawakamii* and *P. tomentosa.*

The trees of paulownia are characterized by a wide range of uses, although the objectives of the establishment of a plantation are to improve degraded soils, the use of animal manure, rapid biomass production or cellulose wood for paper production.

Paulownia plants tolerate a fairly wide range of temperatures and humidity, are adapted to adverse soil conditions, are light-loving, are tolerant to abiotic stressors.

The cultivation technology is simple, based on the use of a valuable biological material adapted to specific local conditions, on the use of fertilizers and irrigation water, especially in the early years of life.

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