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Selection of high-performing *Paulownia tomentosa* Sted. breeding strains for cultivation in south-eastern Poland

Abstract. Climatic constraints, particularly winter temperatures, strongly influence the successful cultivation of paulownia plants outside their native range. Therefore, the aim of the present study was to select fast-growing and winter-hardy royal paulownia strains better adapted to Polish climatic conditions. Paulownia plants were grown under stressful conditions, including high planting density, without mineral fertilisation, no irrigation, and no weeding. Based on the quotient method, the three paulownia strains were selected for cultivation in south-eastern Poland. The 'LuP' strain is most promising, as it showed the highest productivity and winter hardiness, with a four-year index exceeding 36. The 'LuD' and 'We' strains are also recommended for cultivation in moderate climate zones, for which the four-year strain indices were approximately 31. These plants also exhibited high productivity and winter survival, confirming their value as breeding material. The selection of high-performing paulownia strains better adapted to local climatic conditions will significantly impact the productivity and profitability of plantations.

Keywords: royal paulownia, selection breeding, quotient method, winter hardiness, biomass potential, woody production

INTRODUCTION

Paulownia is a woody plant native to south-eastern China [Zhu et al. 1986]. The genus *Paulownia* includes nine species, namely *P. albiphloea* Z.H. Zhu sp. nov., *P. australis* Gong Tong., *P. catalpifolia* T. Gong ex D.Y. Hong, *P. elongata* S.Y. Hu, *P. fargesii* Franch., *P. fortunei* (Seem.) Hemsl., *P. kawakamii* T. Itô, *P. taiwaniana* T.W. Hu & H.J. Chang and *P. tomentosa* Steud. [Yadav et al. 2013]. Due to their exceptionally rapid growth, high biomass productivity, and valuable timber, paulownia species have attracted considerable attention for forestry, agroforestry, and bioenergy production in many regions of the world [Azzarello et al. 2012, López et al. 2012, Zuazo et al. 2013].

Paulownia is considered one of the most promising fast-growing tree species because of its wide range of applications in various economic sectors. Its intensive growth rate, high biomass productivity, and adaptability to diverse environmental conditions have increased interest in its use for biomass and bioenergy production, in the wood industry, and in the cellulose and paper sector [Ayan et al. 2006,

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Akyildiz and Kol 2010, Azzarello et al. 2012, López et al. 2012, Zuazo et al. 2013]. Paulownia also offers important agricultural and environmental benefits. Its large leaves are nutrient-rich and decompose rapidly, making them a valuable source of green manure that can improve soil fertility and organic matter content [Woźniak et al. 2018]. In addition, the foliage can be used as animal feed due to its relatively high protein content and favourable mineral composition [Al-Sagheer et al. 2019]. Its ability to absorb and accumulate heavy metals also makes paulownia useful for phytoremediation and the restoration of degraded or contaminated land [Doumett et al. 2008, Stankovic et al. 2009, Wang et al. 2010]. Furthermore, these plants also have medicinal, ornamental, and beekeeping applications [Zhu et al. 1986, Icka et al. 2016].To ensure rapid growth and high productivity, paulownia cultivation requires appropriate site selection and management practices. Plants grow best on fertile, well-drained sandy soils with a groundwater level of less than 1.5 meters [Woods 2008, Danciu et al. 2016]. The optimal soil pH range is 6.5–7.5 [Woods 2008]. This species cannot tolerate very dry, very compact, or waterlogged soils, as these conditions can severely limit growth and survival [Woods 2008]. Before planting, the soil should be thoroughly prepared through deep ploughing and effective weed control, as young plants are sensitive to weed competition. Adequate water availability is particularly important, especially during the first two to three years after planting [Barton et al. 2007]. In regions with insufficient rainfall, supplemental irrigation may be required. However, excessive soil moisture and waterlogging must be avoided, because they can impair root development and overall tree performance [García-Morote et al. 2014]. Young paulownia trees are particularly sensitive to late spring frosts and should therefore be planted once the risk of severe frost has passed [Innes 2009]. Protection from strong winds may also be beneficial during the early stages of growth [Woods 2008]. As *Paulownia* is a light-demanding species, plantations should be established in full sun, since shade significantly reduces growth and biomass production [Zhu et al. 1986, Owfi 2017]. Under favourable environmental conditions and appropriate management, *Paulownia* plants can achieve exceptionally rapid growth rates and produce harvestable timber within a relatively short rotation period compared with many traditional forestry species.

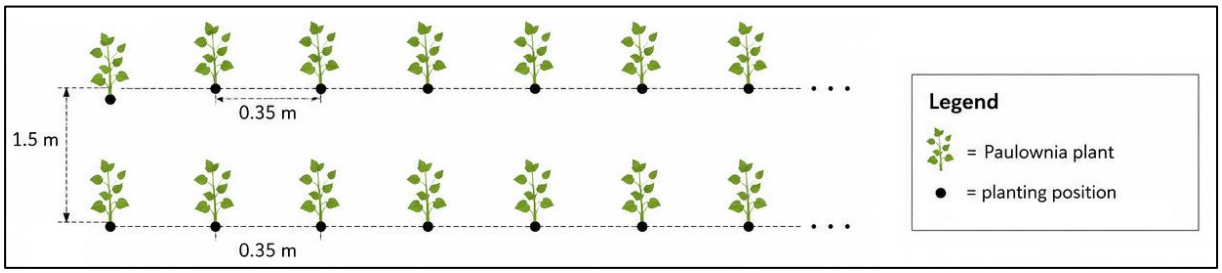
Paulownia is a very thermophilic genus that grows in warmer climates than those in Poland [Litwińczuk and Jacek 2023]. Climatic constraints, particularly winter temperatures, strongly influence the successful cultivation of paulownia plants outside their native range. The climate in south-eastern Poland is characterised by relatively cold winters, and temperatures may periodically fall below the tolerance limits of most *Paulownia* species. As a result, low-temperature stress is one of the main factors limiting the establishment, growth, and long-term survival of these trees in our region. Among all species in the genus *Paulownia*, *P. tomentosa* exhibits the highest frost tolerance, surviving temperatures just below -20°C [Donald 1990, Woods 2008]. Even so, this species may sustain frost damage during exceptionally severe winters. The remaining species are much less frost-resistant. Minimum tolerated temperatures range from –15°C to –18°C for *P. catalpifolia* and *P. elongata*, from –5°C to –10°C for *P. australis*, *P. fargesii*, *P. fortunei* and *P. kawakamii*, to approximately –5°C for *P. albiphloea* and to just +2°C for *P. taiwaniana* [Zhu et al. 1986, Barton et al. 2007].

In light of these climatic limitations, it is particularly important to identify and develop paulownia genotypes better adapted to the environmental conditions of Central and Eastern Europe. Breeding and selection programmes increasingly focus on obtaining plant material that combines rapid growth and high biomass yields with enhanced winter hardiness and frost resistance. Such genotypes could substantially increase the profitability of cultivating paulownia for timber production, renewable biomass generation, and agroforestry applications in temperate climates. Therefore, the aim of the present study was to select strong-growing, high-yielding, and winter-hardy royal paulownia strains with the potential for successful cultivation under the climatic conditions of south-eastern Poland.

MATERIAL AND METHODS

In June 2014, a field experiment was established in Świlcza, near Rzeszów (50°04'N 21°54'E), in IIIa-quality organic soil. Thirteen strains of *Paulownia tomentosa* were obtained from seeds collected from trees growing in arboreta, botanical gardens, or on private property [Jacek and Litwińczuk 2025]. A randomized complete block design was established. Paulownia plants were planted in double-row plots with 1.5 m between the rows and 0.35 m between plants within each row (Figure 1). Each strain was represented by 36 plants. The paulownia plants were grown under adverse conditions, with no mineral fertilisation, irrigation, or weed control and at a high planting density.

Figure 1. Experimental design of the *Paulownia* field trial established in Świlcza



The research was conducted from 2014 to 2018. Basic biometric measurements were taken of the paulownia plants. After the vegetation period, the length and basal diameter of the longest shoot, as well as the total shoot length and number of shoots, were determined. Fresh and dry shoot mass were also determined. After each winter period, the real winter hardiness of the paulownia plants was assessed.

The quotient method, as described by Paszkowska and Mazurkiewicz [1967] and Kuraczyk et al. [2003], was used to select paulownia strains exhibiting the highest growth rate, productivity, and winter hardiness during the four-year studies. For each trait, the average value obtained for a given strain was divided by the overall average calculated across all thirteen strains. The sum of these quotient values determines the strain index. This index was then used to identify the best strains. Advanced statistical analysis was conducted using the Statistica 13.0 software package. The similarity among the studied paulownia strains was evaluated using Ward's method based on Euclidean distances. In addition, principal component analysis (PCA) was performed. All statistical tests were considered significant at $p < 0.05$.

RESULTS

Meteorological records of temperature and precipitation were provided by the University of Rzeszów meteorological station (Table 1). The average annual air temperature ranged from 9.2°C in 2017 to 10.2°C in 2014. The average vegetation temperature was relatively stable, ranging from 17.1°C (2016) to 17.7°C (2015). The most severe winter conditions occurred at the turn of the 2016/17 season. During this time, the minimum ground temperature reached –30°C. In contrast, minimum temperatures in 2014/15, 2015/16, and 2017/18 were close to –20°C. Annual precipitation ranged from 370 to 443 mm, whereas precipitation during the vegetation period was from 157 to 275 mm. Thus, the vegetation periods from 2014 to 2017 were not considered optimal for the growth of paulownia plants. Droughts occurred most frequently. The year 2016 was especially harsh due to exceptionally low annual precipitation.

The *Paulownia* strains studied differed significantly in growth, biomass production, and winter hardiness. This allowed for selection of the most suitable strains for further breeding work. After the first year of growth in 2014, three paulownia strains showed the most intensive growth and greatest winter hardiness: 'Po', 'We', and 'LuD' (Table 2). Based on the quotient method, the 'Po' strain had the highest score. These plants had the greatest number and total length of all shoots compared to other strains. The 'We' strain had a slightly lower index. It was characterised by the fastest shoot length growth. Conversely, the 'LuD' plants had the largest diameter at the shoot base and were definitely the most winter-hardy. Trait values for these three strains were up to 15% higher than the average for all strains.

Table 1. Meteorological conditions in Rzeszów in 2014–2017

Year	Average annual temperature (°C)	Average vegetation temperature (°C) (V–IX)	Minimum ground temperature (°C)	Sum annual precipitation (mm)	Sum vegetation precipitation (mm) (V–IX)
2014	10.2	17.4	–20.6	426.1	275.2
2015	10.0	17.7	–20.0	394.8	195.9
2016	9.4	17.1	–30.4	442.9	157.2
2017	9.2	17.6	–20.5	370.1	182.8

Table 2. Quotient-based assessment of paulownia breeding strains after the first growing season (2014)

Strain	Strain index					
	shoot length	total shoot length	Number of shoots	shoot base diameter	overwintering	sum
Bd	1.08	1.08	1.02	1.07	0.99	5.24
Bg	1.05	0.98	0.91	1.01	0.99	4.94
Bl	0.90	0.90	1.00	0.92	1.05	4.77
Cr	0.77	0.68	0.84	0.85	0.72	3.86
Kr	0.99	0.87	0.84	1.04	0.99	4.73
LuB	0.91	1.03	1.14	0.95	1.02	5.05
LuD	1.09	1.06	0.95	1.13	1.15	5.38
LuP	1.04	1.12	1.14	0.97	1.02	5.29
Po	1.03	1.14	1.15	1.04	1.09	5.45
Ru	1.06	1.12	1.09	1.12	0.99	5.38
Wa	0.95	0.96	1.00	0.91	0.95	4.77
We	1.13	1.11	1.01	1.06	1.12	5.43
Wr	1.01	0.96	0.93	0.95	0.92	4.77
Average for 13 strains	1.00	1.00	1.00	1.00	1.00	5.00

In the second year of cultivation in 2015, two additional biomass-yield-determining traits were considered in the evaluation of paulownia strains: fresh and dry stem mass. The numerical values for the strains ranged from approximately 5.8 to 9.8. Among the strains, 'LuP', 'We', and 'LuD' exhibited more intensive growth, higher biomass productivity, and better winter hardiness than the other. The 'LuP' strain had the highest index due to its high yield potential (Table 3). Its stem mass was almost 70% above the average. A high numerical value was also determined for the 'We' strain. These plants were characterised primarily by their highest winter hardiness after two winters compared to the other plants. The 'LuD' strain also had a relatively high index.

In the third year of cultivation (2016), the same traits were used to evaluate the 13 strains as in the previous year of the study. The following three paulownia breeding strains were selected: 'LuP', 'LuD', and 'We'. Notably, 2016 was characterised by the lowest vegetation-season temperature, the lowest growing-season precipitation, and the most severe frost conditions of the entire study period.

Despite these adverse conditions, the 'LuP' strain had by far the highest numerical value, at just over 12. Plants from this strain exhibited the fastest growth, the highest yield, and the greatest winter hardiness compared to the other strains. Some trait values were up to 2.5 times higher than the overall average (Table 4). Meanwhile, plants from the 'LuD' and 'We' strains also exhibited high values for biometric and yield-forming traits, as well as an excellent ability to survive winter. Additionally, the fresh and dry shoot mass of the 'LuD' and 'We' strains was approximately 1.5 times higher than the average determined for all strains (Table 4).

Table 3. Quotient-based assessment of paulownia breeding strains after the second growing season (2015)

Strain	Strain index							
	shoot length	total shoot length	number of shoots	shoot base diameter	fresh shoot mass	dry shoot mass	overwintering	sum
Bd	0.90	0.86	1.00	0.93	0.84	0.77	1.02	6.32
Bg	0.88	0.82	0.83	0.92	0.83	0.82	0.95	6.05
Bl	0.90	0.67	0.70	0.90	0.72	0.83	1.05	5.77
Cr	0.88	0.85	0.93	1.00	0.91	0.85	0.70	6.12
Kr	1.01	0.97	0.94	1.00	0.98	1.04	1.05	6.99
LuB	0.96	1.00	1.06	0.99	0.99	1.02	1.02	7.04
LuD	1.14	1.36	1.28	1.06	1.24	1.15	1.12	8.35
LuP	1.31	1.54	1.21	1.31	1.69	1.66	1.09	9.81
Po	0.92	0.87	0.93	0.88	0.87	0.84	1.05	6.36
Ru	0.91	0.79	0.91	0.94	0.81	0.81	0.88	6.05
Wa	1.01	0.92	0.94	1.01	0.88	0.92	1.02	6.70
We	1.22	1.33	1.18	1.13	1.37	1.42	1.16	8.81
Wr	0.88	0.89	0.99	0.91	0.87	0.87	0.91	6.32
Average for 13 strains	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7.00

Table 4. Quotient-based assessment of paulownia breeding strains after the third growing season (2016)

Strain	Strain index							
	shoot length	total shoot length	number of shoots	shoot base diameter	fresh shoot mass	dry shoot mass	overwintering	sum
Bd	0.91	0.75	0.71	0.88	0.55	0.55	0.97	5.32
Bg	0.98	0.80	0.75	1.01	0.81	0.78	0.88	6.01
Bl	0.97	0.74	0.88	0.93	0.58	0.60	1.05	5.75
Cr	0.94	0.81	1.02	1.02	0.95	0.96	0.76	6.46
Kr	0.97	0.92	0.78	0.95	0.60	0.65	1.18	6.05
LuB	0.97	1.07	1.02	0.97	1.34	1.35	1.14	7.86
LuD	1.15	1.36	1.34	1.08	1.52	1.58	1.18	9.21
LuP	1.23	1.71	1.36	1.21	2.62	2.65	1.30	12.08
Po	0.90	0.78	1.02	0.90	0.51	0.53	1.01	5.65
Ru	0.86	0.72	0.77	0.86	0.46	0.47	0.76	4.90
Wa	0.94	0.75	0.71	0.97	0.67	0.69	0.88	5.61
We	1.04	1.16	1.31	1.09	1.65	1.42	1.09	8.76
Wr	0.92	0.75	0.89	0.95	0.71	0.76	0.80	5.78
Average for 13 strains	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7.00

As in the previous two years, three breeding strains were selected in the fourth year of cultivation (2017): 'LuP', 'We', and 'LuD'. The 'LuP' strain had the highest index, reaching almost 9.5. These plants had the highest annual shoot growth and very high productivity. They also showed the greatest winter

hardiness among the strains (Table 5). Trait values for these plants were almost 60% higher than the average for all strains. The 'We' strain had a slightly lower index, at almost 8.5. On average, these plants had 30% more shoots and were 30% heavier than the other strains. The 'LuD' strain also had a relatively high numerical value, slightly over 8.4.

In the four-year study, the 'LuP', 'We' and 'LuD' strains exhibited the most intensive growth and the highest biomass yield. They also showed the highest winter hardiness (Figure 2). The 'LuP' strain had the highest total index, which was slightly over 36.5. High 4-year indices were also found for the 'We' and 'LuD' strains, at slightly over 31. A relatively high total numerical value was also found for the 'LuB' strain. However, these plants exhibited weaker growth, lower yields, and lower winter hardiness than the three other high-performing strains.

Table 5. Quotient-based assessment of paulownia breeding strains after the fourth growing season (2017)

Strain	Strain index							
	shoot length	total shoot length	number of shoots	base diameter of the strongest shoot	fresh shoot mass	dry shoot mass	overwin-tering	sum
Bd	0.98	0.76	0.79	1.00	0.86	0.86	0.96	6.21
Bg	0.94	0.89	0.87	0.93	0.80	0.80	0.87	6.10
Bl	1.01	0.79	0.87	0.96	0.90	0.94	1.00	6.47
Cr	1.01	0.87	0.99	1.08	1.14	1.15	0.79	7.03
Kr	0.94	0.82	0.87	0.96	0.69	0.75	1.18	6.21
LuB	0.95	1.07	1.13	0.95	0.94	0.94	1.18	7.16
LuD	1.14	1.39	1.18	1.02	1.20	1.27	1.22	8.42
LuP	1.15	1.39	1.39	1.13	1.58	1.41	1.35	9.40
Po	0.95	0.93	0.85	0.92	0.83	0.86	1.00	6.34
Ru	0.96	0.89	0.82	1.08	1.03	1.07	0.70	6.55
Wa	0.86	0.71	0.85	0.95	0.78	0.75	0.92	5.82
We	1.07	1.35	1.26	1.03	1.31	1.33	1.09	8.44
Wr	0.96	0.83	0.88	1.02	0.93	0.90	0.74	6.26
Average for 13 strains	1.00	1.00	1.00	1.00	1.00	1.00	1.00	7.00

Figure 2. Sum of the index of the studied strains in 2014–2017

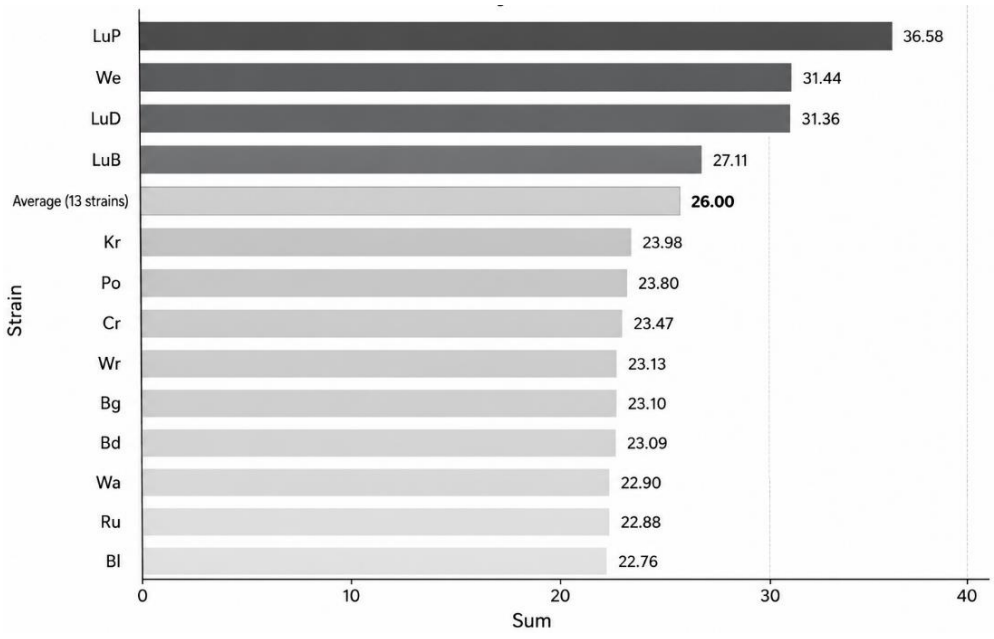


Figure 3. Comparison of the three selected strains ('LuP', 'LuD' and 'We') with the other ten strains

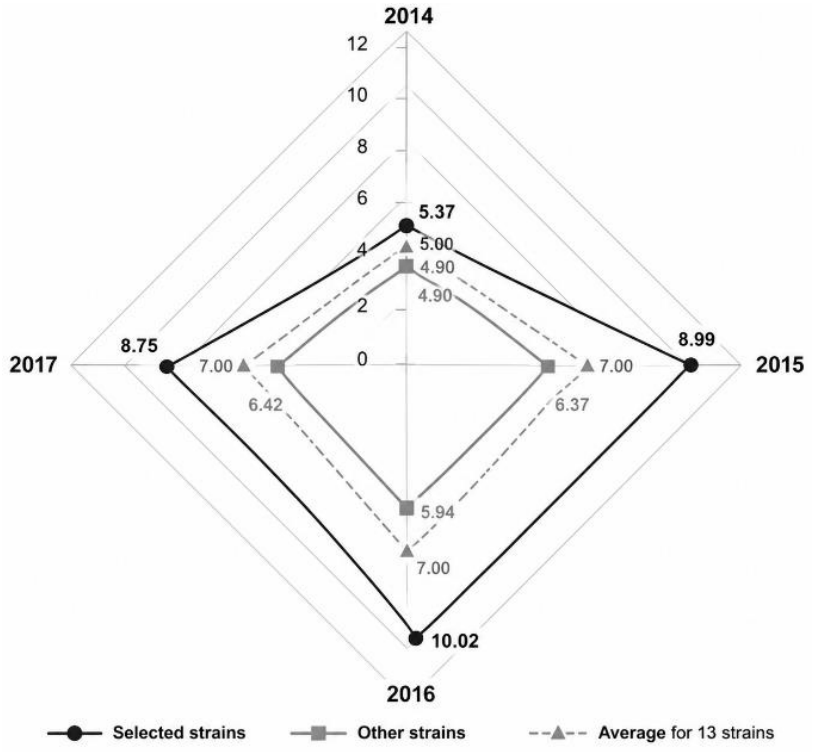
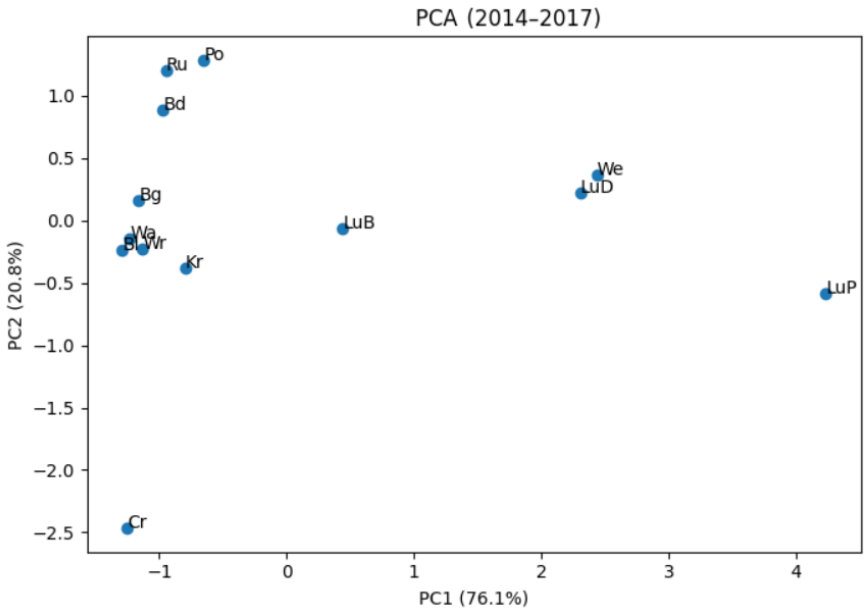


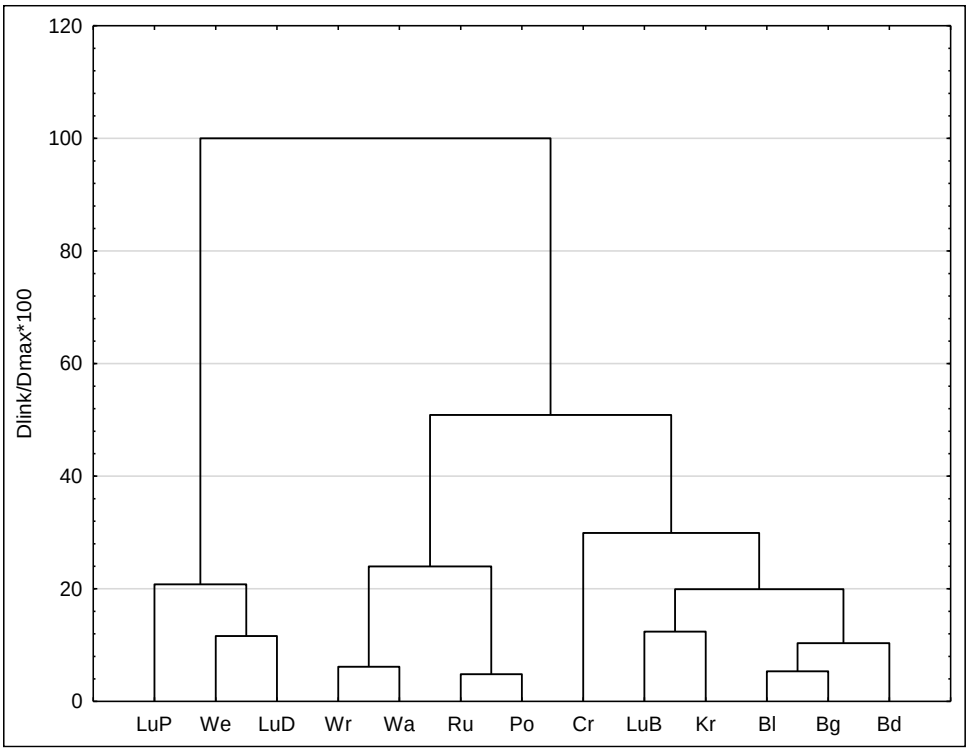
Figure 4. Principal component analysis of 13 strains based on annual values recorded between 2014 and 2017



Throughout the study period, the three selected strains ('LuP', 'We' and 'LuD') consistently exhibited higher values than the other strains (Figure 3). The largest difference occurred in 2016. High-yielding strains achieved, on average, almost twice as much as lower-yielding strains. Principal component analysis also confirmed that the 'LuP' strain had the greatest biomass yield potential and was the most winter-hardy (Figure 4). 'We' and 'LuD' strains formed the second group of high-yielding paulownia

strains. Plants of the ‘LuB’ strain were located between the high- and low-yielding groups. The remaining weaker strains formed a relatively compact group with similar biometric and yield-forming traits. This relationship was also confirmed in cluster analysis using Ward's method (Figure 5). The studied paulownia strains were divided into three groups. The first group consisted of ‘LuP’, ‘We’ and ‘LuD’ strains. These three strains were clearly distinguishable from the other strains by their growth intensity, yield, and winter survival. The second group comprised ‘Wr’ and ‘Wa’, as well as ‘Ru’ and ‘Po’ strains. ‘LuB’, ‘Kr’, ‘Bl’, ‘Bg’, and ‘Bd’ formed a third cluster. Additionally, this group included the ‘Cr’ strain.

Figure 5. Dendrogram of the studied paulownia strains’ similarity



DISCUSSION

Despite the growing global interest in *Paulownia* cultivation, research under Polish climatic conditions remains limited. Most studies in our country have focused on paulownia growth optimisation [Lisowski and Porwisiak 2017, 2018, Liszewski and Bąbelewski 2018a, 2018b, Smarul et al. 2018]. Although these studies have provided valuable insights into cultivation requirements and crop-planting strategies to maximise biomass and wood production, considerably less attention has been given to the comparative evaluation and selection of the most valuable species, hybrids or genotypes. This is particularly important because significant differences have been shown among paulownia strains in growth dynamics, biomass productivity, stress tolerance, and winter survival [Jacek and Litwińczuk 2016, 2025]. These variations suggest that genotype selection could significantly affect plantation productivity and economic profitability, particularly in regions with variable climatic conditions such as Poland. Therefore, the aim of the present study was to select intensive-growing, high-yielding, and winter-hardy royal paulownia strains for successful cultivation under the climatic conditions of south-eastern Poland.

A field experiment was established in Poland to support selection and breeding work on royal paulownia under stressful conditions, including dense planting, without mineral fertilization, irrigation, or weed control. The study focused on selection and breeding work, not on optimising plant cultivation. Paulownia is thermophilic, and low winter temperatures may be the main factor limiting its cultivation in Poland. Royal paulownia is the most frost-tolerant species, surviving temperatures slightly below –20°C [Zhu et al. 1986, Donald 1990, Woods 2008], according to some reports, even down to –25°C [Innes 2009, Icka et al. 2016]. However, these data refer to several-year-old trees. Younger, insufficiently lignified specimens are more susceptible to frost damage. According to Innes [2009], young paulownia plants may die below –10°C. Further research is therefore required to identify genotypes with superior frost resistance, survival rates, and productivity. Such studies are particularly important for Poland, where severe winter conditions may significantly affect plantation establishment and economic viability.

In the four-year study period, three high-performing paulownia strains were selected. The 'LuP' strain is the most promising for cultivation in south-eastern Poland. These plants showed the most intensive growth and highest biomass production, and this assessment is strengthened by their winter hardiness. After four winters, 86% survived and grew at a much higher density per unit area than the other strains. Importantly, plant competition did not limit their growth and yield. The superior performance of the 'LuP' strain was maintained even in 2016, which had the lowest vegetation-season temperature, the lowest growing-season precipitation, and the most severe frost conditions recorded during the study period. An additional experiment was conducted on sandy soil of the VI quality class in Grochowe near Mielec [Jacek and Litwińczuk 2025]. Despite the poorer soil quality and less favourable growth conditions at this site, the 'LuP' strain also showed high productivity and was identified as one of the most promising strains. This demonstrates the strain's high adaptability and resilience to adverse environmental conditions.

The 'LuD' and 'We' strains also exhibited relatively high index values in each year of the study. Plants from these strains demonstrated satisfactory winter hardiness after the first two years of cultivation due to milder winters. However, after experiencing more severe winter conditions in the following two years, more dead specimens were observed. Nevertheless, these plants stood out for their significantly higher yields compared to the other ten strains. Thus, the 'LuD' and 'We' strains should also be recommended for cultivation in moderate climate zones. They demonstrated uniform and very vigorous growth over the four years of the study. It is worth emphasizing that even higher biomass yield can be expected under optimal growth conditions. Importantly, the 'LuD' and 'We' strains also performed rapid growth, higher biomass yield, and better winter survival in the two-year experiment conducted in Grochowe [Jacek and Litwińczuk 2025]. Multivariate statistical analyses, including principal component analysis and cluster analysis, confirmed the distinct position of the 'LuP', 'We', and 'LuD' strains. They clearly separated them from the remaining, less productive genotypes.

Furthermore, the 'LuB' strain ranked fourth based on the quotient method and principal component analysis. This strain is a sister lineage to 'LuD', as the mother plants of the aforementioned strains grow nearby and cross-pollinate. However, over the four-year study period, the 'LuB' strain plants yielded less and overwintered less than the 'LuD' strain plants. For the remaining nine families, a significant problem was the low survival rate of plants after winter. In fact, more than half of the plants died. Despite less plant competition for water, minerals, and light, no stronger growth or higher yields were observed in subsequent years.

CONCLUSIONS

1. Significant differences among the studied *Paulownia tomentosa* breeding strains in terms of growth dynamics, biomass productivity, and winter hardiness indicate substantial genetic variation and the potential for effective selection in a temperate climate.

2. The 'LuP', 'We', and 'LuD' strains consistently ranked among the high-performing genotypes throughout the evaluation period. These strains exhibited rapid growth, higher biomass yield, and better winter survival than the other strains.

3. The 'LuP' strain showed the greatest overall breeding value, achieving the highest total selection index. Its combination of rapid growth, high stem biomass production, and excellent winter hardiness makes it the most promising strain for further breeding and commercial cultivation in Poland.

4. The 'We' and 'LuD' strains also exhibited high productivity and winter survival, confirming their value as breeding material in regions with moderate climatic conditions and periodic winter stress.

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