Folia Forestalia Polonica, Series A – Forestry, 2022, Vol. 64 (3), 131–142

ORIGINAL ARTICLE

DOI: 10.2478/ffp-2022-0013

Comparative studies of the macro- and microstructures of stump-root wood and stemwood

Serhiy Gayda[1] ✉, *Orest Kiyko*, *Mykola Guz*

Ukrainian National Forestry University, Henerala Chuprynky 103, Lviv 79057, Ukraine,
e-mail: serhiy.hayda@nltu.edu.ua

ABSTRACT

It is found that the existing problem of wood resources can be partially solved by attracting additional reserves, in particular, stump-root wood (SRW). In order to apply SRW in woodworking and to fill the scientific base with indicators of the macro- and microstructures of the stump-root systems of individual species, studies were carried out on the main characteristics that are decisive for using composite materials in the industrial production. Based on the study results, it was found that there are differences in the internal structure between SRW and stemwood (SW). It was found that in all species, the width of annual rings in the SRW was greater than that in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 84.62%; in spruce (*Picea abies* Karst.) – by 73.68%; in fir (*Abies alba*) – by 93.75%; in aspen (*Populus tremula* L.) – by 35.71% and in birch (*Betula pendula* Roth.) – by 105.00%. It has been found that the content of late wood in the SRW of coniferous tree species is less than that in the SW, on average by 20–25%, and the number of annual rings per 1 cm in the SRW is 40–52% less than in the SW. Differences in the microscopic structure between SRW and SW are revealed, which consist in the difference in the size of tracheids in softwoods and of vessels and fibres of libriform in hardwoods. It was found that the transverse dimensions of early tracheids in the SRW were larger than in the SW, in particular, in the radial direction by 19–33% and in the tangential direction by no more than 15%, and the interval of dimensions in the radial direction was 1.5–2.5. It was found that the early tracheids of root wood had thinner walls (by 19–28%) and a larger internal cavity (by 15–25%) compared to similar elements of SW. It was revealed that the diameters of vessels and fibres of libriform in SRW are greater than in SW, in particular, in aspen (*Populus tremula* L.) – by 20.41% for vessels and by 12.95% for libriform fibres and in birch (*Betula pendula* Roth.) – by 20.69% for vessels and by 18.41% for libriform fibres. The practical significance of the studies lies in the fact that the obtained characteristics of the structural components of the SRW can be used to predict the strength indicators of composite materials.

KEY WORDS

stump-root wood, annual layers, late wood, tracheids, libriform fibres, macro- and microstructures, *Pinus sylvestris* L., *Picea abies* Karst., *Abies alba*, *Betula pendula* Roth., *Populus tremula* L.

Received 28 April 2022 / Accepted 6 May 2022

INTRODUCTION

Today, as always, the issue of the integrated use of wood resources, in particular, logging residues (Hakilla 1976; Ratajczak 2013), post-production waste (Gayda and Maksymiv 2007; Ratajczak et al. 2018) and post-consumer wood (Gayda 2016; Gayda and Kiyko 2020a, 2020b, 2021), remains relevant. Solving the problem of processing these additional resources will allow, to some extent, to save primary raw materials and reduce the load on the environment (Gayda 2013). A promising direction that will partially reduce the shortage of wood in Ukraine is the utilisation of stump-root wood (SRW) for the production of composite materials, including particleboard (chipboard), with the annual reserves of SRW averaging 2.2 million m^3 (Nikishov 1985). The use of SRW is possible for no more than 40–50% the allotted area. The use of significant amounts of SRW on the site can cause irreparable harm to the environment: mixing of soil horizons, extracting a significant amount of organic matter from the soil, disturbing the microrelief of the site, destroying natural renewal and so on. The use of this raw material will make it possible to obtain additionally almost 500,000 m^3 of boards, but today it is practically not used for the specified purposes. One of the reasons hindering the use of this raw material as the main structural component for particleboard is the lack of knowledge of its internal structure and properties. In order to apply SRW in woodworking and fill the scientific base with indicators of macro- and microstructure of stump-root systems of individual tree species, it is necessary to study the main characteristics that are crucial for the material use in the production of composite materials. Thus, the study of these issues and, on their basis, obtaining sound reference data on the internal structure of stump-root systems will solve the pressing problem of replenishing the raw material base of woodworking enterprises by using this additional wood resource for manufacturing particleboards (Nikityuk et al. 1993a, 1993b).

Scientists have been studying the structure and properties of wood of individual tree species, in particular, their roots, for over a hundred years. The work of Chernyaev (1864) is well-known. It is also necessary to note the work of Pislar (1936), who studied the anatomical structure of the roots of fruit trees. His studies were of a comparative anatomical nature, which allowed him to discover a number of anatomical features that can be used to distinguish not only genera, but even species of fruit trees. He was not engaged in the study of industrial species of trees. In coniferous species, the bulk of the root wood consists of early and late tracheids (Chavchavadze 1979). In addition, wood rays, wood parenchyma and resin ducts are found here. But in the structure of the roots, characteristic peculiarities are also observed. The roots do not have a pith; in the centre, there is a primary wood with one or more resin ducts. Heartwood is almost never formed in the roots.

In the studies of Perelygin (1954), it was noted that the wood rays in the root wood are wider and are located more densely than in the stemwood (SW). In the roots of spruce (*Picea abies* Karst.), larch and pine (*Pinus sylvestris* L.), there occur medullary rays without horizontal tracheids. In fir (*Abies alba*), the medullary rays have marginal parenchymal cells, strongly elongated along the ray, with similar outer walls. The resin ducts in the wood of the roots are entwined with a large number of cells of the leading parenchyma, forming continuous bands or one-sided accumulation. The properties of fibres in SRW are somewhat different from the properties of fibres in SW. The shortest tracheids are located in the root collar – from 1.87 to 2.43 mm – as described by Geles (1978). As the distance from the centre of branching of the root system increases, the tracheids' length increases. On a straight section of the root, the length of tracheids does not differ from their length in SW, which is 3.3–4.1 mm. On average, the tracheids of the SRW are somewhat shorter than those in the SW. Scientists have not investigated the transverse dimensions of the tracheids.

Some comparative studies of different parts of birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.) trees were conducted by Mutovina et al. (1983), which noted differences in fibre length and cell wall thickness. However, the diameters of vessels and libriform fibres, in particular, in the roots of these species, were not investigated. In the studies of Vintoniv et al. (2007) and Yatsenko-Khmelevskyy (1954), the internal structure of SW of some species is specified, but the features of macro- and microstructures of SRW are not presented.

In his work, Howard (1974) noted the differences between the anatomical internal structure of root wood and SW, which manifested itself when they were used in a crushed form. But the research itself was not carried out by the author. A detailed catalogue for the identification of broadleaved species by microscopic characteristics of SW was presented by Wheeler et al. (1989). They did not conduct comparative studies on the internal structure of root wood and SW.

Thus, the internal structure of root wood has some differences compared to the structure of SW. Structural peculiarities are observed both at the macro- and microscopic levels, that is, in the structure of individual elements, in their arrangement and volume ratio. But, as a brief analysis of literature sources has shown, the structure of SRW, especially of those species that are mainly used for the production of composite materials, has not yet been sufficiently studied.

The aim of the study is to investigate the differences in the macro- and microstructures between SRW and SW.

The object of the study is the internal structure of SRW and SW of the main species.

The subject of the study is macrostructure: annual layers and microstructure: transverse dimensions of early and late tracheids and diameters of vessels in the SRW of coniferous species – pine (*Pinus sylvestris* L.), spruce (*Picea abies* Karst.) and fir (*Abies alba*) – and libriform fibres in broadleaved species – aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth.).

Research objectives: 1) To establish the differences between the annual layers of the SRW and SW by determining the number of annual layers, the average width of the annual layers and the percentage of late wood. 2) To determine the sizes of tracheids in the SRW of coniferous species – pine (*Pinus sylvestris* L.), spruce (*Picea abies* Karst.) and fir (*Abies alba*) – and the diameters of the vessels and fibres of the libriform in the SRW of hardwoods – aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth.). 3). To compare the internal structure of stump-root systems with the SW of the studied species.

MATERIAL AND METHODS

As is known, wood particles are the main component of chipboard and have a significant effect on their properties. Therefore, their internal structure should be considered as an important characteristic of these reinforcing elements. Since the trunk and roots perform partially different functions in a growing tree, they obviously have a different internal structure that needs to be studied.To compare the internal structure of SRW and SW, microscopic studies were carried out. We analysed those elements of wood that can be distinguished under a microscope and which characterise porosity, that is, early and late tracheids in conifers, large and small vessels and libriform fibres in hardwoods.The macrostructure was studied with the help of a magnifying glass, in particular, the structure of annual rings, which are characterised by indicators such as the number of annual rings per 1 cm, the average width of annual rings and the percentage of late wood (GOST 16483.18:1972). The visibility of annual rings and sharpness of the transition from early to late wood within the annual ring were also studied. To compare the macro- and microstructures of the SW and SRW, model trees of spruce (*Picea abies* Karst.), fir (*Abies alba*), pine (*Pinus sylvestris* L.), aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth.) were selected according to GOST 16438.6:1980 and ISO 3129:2019, and for each species, wood samples were taken from three trees. Three stump-root system samples were cleared from the ground and prepared for research. The SRW samples were taken from the area of the root collar and at a distance of 50–60 cm from the transverse root discs: for pine (*Pinus sylvestris* L.) and fir (*Abies alba*), from the roots of vertical orientation and for spruce (*Picea abies* Karst.), from the roots of horizontal orientation. The SW samples in the form of discs were obtained from sections at a height of 1.3 m from the root collar. Two blocks from each stem disc and two to seven blocks from each root disc were examined. A microtome was used to cut thin layers. After pre-cooking in water with the addition of glycerol, the sections were cut perpendicular to the fibres. Thin sections of spruce (*Picea abies* Karst.), fir (*Abies alba*), pine (*Pinus sylvestris* L.), birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.) were stained with a solution of safranin, dehydrated in alcohol, purified from xylene and made into preparations by placing them between glass plates. To measure the size of block of cells, we used wood from growth rings 1 and 2 closest to the pith, rings 9 and 10, and the last two rings closest to the bark. An MBI-1 biological microscope with a total magnification of 56–1350 times was used for the experiments. Photographing was carried out using the MFK-20 photo attachment with a Zenith-12 D camera. Statistical processing of research results was carried out according to the recommendations of GOST 16483.0:1989 using statistical program.

Results

The results of comparative studies of the macrostructure of SRW and SW are given in Table 1.

It is found that in all species, the width of the annual rings in the SRW is greater than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 84.62%; in spruce (*Picea abies* Karst.) – by 73.68%; in fir (*Abies alba*) – by 93.75%; in aspen (*Populus tremula* L.) – by 35.71% and in birch (*Betula pendula* Roth.) – by 105.00%. It should also be noted that the content of late wood in the SRW of conifers is lower than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 19.60%; in spruce (*Picea abies* Karst.) – by 27.30% and in fir (*Abies alba*) – by 21.69%, which is

Table 1. Statistics of indicators of the macrostructure of SRW and SW

Wood	Indicators for pine	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
SW	average width of annual rings, mm	41	1.30	1.10	1.45	0.019	9.23	1.44
	number of annual rings in 1 cm, pcs	41	7.60	6.45	8.46	0.025	2.11	0.33
	percentage of late wood, %	23	25.00	21.23	27.84	0.211	4.04	0.84
SRW	average width of annual rings, mm	41	2.40	2.04	2.67	0.037	10.00	1.56
	number of annual rings in 1 cm, pcs	41	4.10	3.48	4.57	0.042	6.59	1.03
	percentage of late wood, %	23	20.10	17.06	22.38	0.156	3.73	0.78
Wood	Indicators for spruce	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
SW	average width of annual rings, mm	41	1.90	1.67	2.13	0.067	22.63	3.53
	number of annual rings in 1 cm, pcs	41	5.20	4.57	5.82	0.153	18.85	2.94
	percentage of late wood, %	23	30.40	26.72	34.02	0.540	8.52	1.78
SRW	average width of annual rings, mm	41	3.30	2.90	3.69	0.044	8.48	1.33
	number of annual rings in 1 cm, pcs	41	3.00	2.64	3.36	0.100	21.33	3.33
	percentage of late wood, %	23	22.10	19.43	24.73	0.976	21.18	4.42
Wood	Indicators for fir	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
SW	average width of annual rings, mm	41	1.60	1.38	1.78	0.023	9.38	1.46
	number of annual rings in 1 cm, pcs	41	6.10	5.26	6.77	0.145	15.25	2.38
	percentage of late wood, %	23	18.90	16.31	20.97	0.882	22.38	4.67
SRW	average width of annual rings, mm	41	3.10	2.68	3.44	0.033	6.77	1.06
	number of annual rings in 1 cm, pcs	41	3.20	2.76	3.55	0.117	23.44	3.66
	percentage of late wood, %	23	14.80	12.77	16.42	0.667	21.62	4.51
Wood	Indicators for aspen	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
SW	average width of annual rings, mm	41	2.80	2.40	3.11	0.039	8.93	1.39
	number of annual rings in 1 cm, pcs	41	3.60	3.09	4.00	0.117	20.83	3.25
SRW	average width of annual rings, mm	41	3.80	3.26	4.23	0.137	23.16	3.62
	number of annual rings in 1 cm, pcs	41	2.60	2.23	2.89	0.061	15.00	2.34
Wood	Indicators for birch	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
SW	average width of annual rings, mm	41	2.00	1.68	2.23	0.050	16.00	2.50
	number of annual rings in 1 cm, pcs	41	5.00	4.20	5.57	0.186	23.80	3.72
SRW	average width of annual rings, mm	41	4.10	3.45	4.57	0.075	11.71	1.83
	number of annual rings in 1 cm, pcs	41	2.40	2.02	2.67	0.089	23.75	3.71

SRW – stump-root wood; SW – stemwood; N – sample volume; M_{aver} – average arithmetic value; M_{min} – minimum value; M_{max} – maximum value; V – coefficient of variation; P – coefficient of accuracy of the experiment.

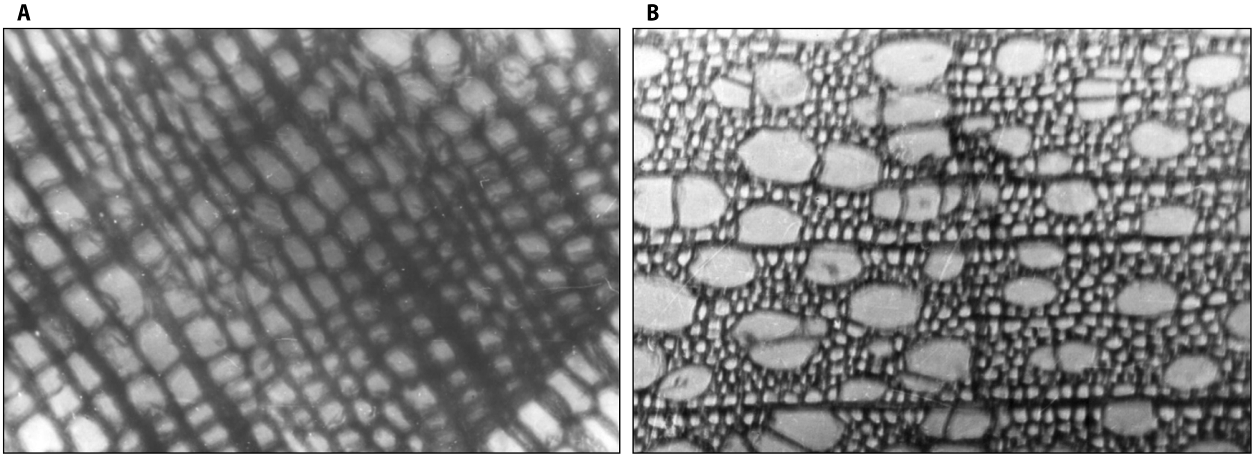

Figure 1. Features of the microstructure of stump-root wood pine (*Pinus sylvestris* L.) (160×) and aspen (*Populus tremula* L.) (70×)

primarily due to the leading function of the stump-root systems of trees.

It is estimated that in all species, the number of annual rings per 1 cm in SRW is less than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 46.05%; in spruce (*Picea abies* Karst.) – by 42.31%; in fir (*Abies alba*) – by 47.54%; in aspen (*Populus tremula* L.) – by 27.78% and in birch (*Betula pendula* Roth.) – by 52.00%. The eccentricity of the annual layers of perennial roots with different deviations can also be observed in microsections (Fig. 1). Individual annual layers show quite different deviations.

An analysis of the microscopic sections of coniferous roots indicated some differences in the shape and size of the main constituent elements – tracheids. Statistics and comparison of characteristics of tracheids of coniferous wood are shown in Table 2.

It was found that in all coniferous species, the transverse dimensions of early tracheids in the SRW were greater than in SW, in particular, in the radial direction in pine (*Pinus sylvestris* L.) – by 32.78% and in spruce (*Picea abies* Karst.) – by 18.67%; in fir (*Abies alba*) – by 22.54%; in the tangential direction

Table 2. Statistics of the size of the tracheid wood roots and trunk of conifers

Wood	Indicators for pine	Layer	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
Stem	radial direction, µm	early	20	36.00	29.80	40.23	0.682	8.47	1.89
		late	20	17.10	14.16	19.11	0.823	21.52	4.81
	tangential direction, µm	early	20	27.40	22.68	30.62	1.199	19.56	4.37
		late	20	28.10	23.26	31.40	1.319	21.00	4.69
	wall thickness, µm	early	20	2.10	1.74	2.35	0.054	11.43	2.56
		late	20	4.40	3.64	4.92	0.101	10.23	2.29
Root	radial direction, µm	early	20	47.80	39.57	53.42	1.811	16.95	3.79
		late	20	19.40	16.06	21.68	0.962	22.16	4.96
	tangential direction, µm	early	20	29.60	24.51	33.08	0.917	13.85	3.10
		late	20	32.40	26.82	36.21	1.610	22.22	4.97
	wall thickness, µm	early	20	1.60	1.32	1.79	0.034	9.38	2.10
		late	20	3.80	3.15	4.25	0.087	10.26	2.29
Wood	Indicators for spruce	Layer	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
Stem	radial direction, µm	early	20	33.20	27.74	37.04	0.521	7.02	1.57
		late	20	20.20	16.88	22.54	0.557	12.33	2.76
	tangential direction, µm	early	20	24.80	20.72	27.67	0.881	15.89	3.55
		late	20	29.90	24.99	33.36	0.973	14.55	3.25
	wall thickness, µm	early	20	3.10	2.59	3.46	0.080	11.61	2.60
		late	20	5.00	4.18	5.58	0.206	18.40	4.11
Root	radial direction, µm	early	20	39.40	32.92	43.96	1.851	21.02	4.70
		late	20	16.60	13.87	18.52	0.796	21.45	4.80
	tangential direction, µm	early	20	25.10	20.97	28.01	1.219	21.71	4.86
		late	20	28.70	23.98	32.02	1.292	20.14	4.50
	wall thickness, µm	early	20	2.50	2.09	2.79	0.038	6.80	1.52
		late	20	3.80	3.18	4.24	0.186	21.84	4.88

Tab. 2 continuous

Wood	Indicators for fir	Layer	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
Stem	radial direction, µm	early	20	35.50	30.25	39.75	1.737	21.89	4.89
		late	20	16.30	13.89	18.25	0.749	20.55	4.60
	tangential direction, µm	early	20	31.50	26.84	35.28	1.677	23.81	5.32
		late	20	26.30	22.41	29.45	1.006	17.11	3.83
	wall thickness, µm	early	20	1.80	1.53	2.02	0.040	10.00	2.24
		late	20	4.10	3.49	4.59	0.116	12.68	2.84
Root	radial direction, µm	early	20	43.50	37.07	48.71	2.102	21.61	4.83
		late	20	17.60	15.00	19.71	0.868	22.05	4.93
	tangential direction, µm	early	20	36.20	30.85	40.54	1.793	22.15	4.95
		late	20	24.90	21.22	27.88	1.219	21.89	4.89
	wall thickness, µm	early	20	1.30	1.11	1.46	0.060	20.77	4.64
		late	20	3.60	3.07	4.03	0.078	9.72	2.17

near pine (*Pinus sylvestris* L.) – by 8.03%; in spruce (*Picea abies* Karst.) – by 1.21% and in fir (*Abies alba*) – by 14.92%. Regarding the late tracheids, we obtained the following results: in the radial direction, there was an increase in pine (*Pinus sylvestris* L.) – by 14.45% and in fir (*Abies alba*) – by 7.98%; in spruce (*Picea abies* Karst.), there was a decrease by 17.82% and in the tangential direction, there was a decrease in all species: in pine (*Pinus sylvestris* L.) – by 15.30%; in spruce (*Picea abies* Karst.) – by 4.01% and in fir (*Abies alba*) – by 5.32%. The interval of the sizes of early and late tracheids both in root wood and in SW in the radial direction was approximately 1.5–2.5.

It should also be noted that the thickness of the walls of early and late tracheids in the SRW of coniferous species was less than that of SW in all species, in particular, in pine (*Pinus sylvestris* L.) – by 23.81% for early tracheids and by 13.64% for late ones; in spruce (*Picea abies* Karst.) – by 19.35% and 24.00%, respectively, and in fir (*Abies alba*) – by 27.78% and 12.20%, respectively (Tab. 2).

There were differences in the dimensions of the vessels and fibres of the libriform, the dimensions of which were larger in the root wood. The vessels of this wood had slightly wider cavities. Statistics and comparison of diameters of vessels and fibres of libriform wood of broadleaved species are given in Table 3. It was found that in broadleaved species, the diameters of vessels and libriform fibres were larger in the SRW than in SW, in particular, in aspen (*Populus tremula* L.) – by 20.41% for vessels and by 12.95% for libriform fibres and in birch (*Betula pendula* Roth.) – by 20.69% for vessels and by 18.41% for libriform fibres.

Table 3. Statistics of the diameters of vessels and libriform fibres in the stump-root wood and stem wood of deciduous species

Wood	Indicators for aspen	N, pcs	M_{aver}	M_{min}	M_{max}	±	V, %	P, %
Stem	vessels, µm	20	98.00	84.48	108.83	0.461	2.10	0.47
	fibre libriform, µm	20	22.40	19.31	24.88	0.241	4.82	1.08
Root	vessels, µm	20	118.00	101.72	131.04	0.528	2.00	0.45
	fibre libriform, µm	20	25.30	21.81	28.10	0.192	3.40	0.76
Wood	**Indicators for birch**	**N, pcs**	**M_{aver}**	**M_{min}**	**M_{max}**	**±**	**V, %**	**P, %**
Stem	vessels, µm	20	87.00	72.14	96.79	0.691	3.55	0.79
	fibre libriform, µm	20	20.10	16.67	22.36	0.224	4.98	1.11
Root	vessels, µm	20	105.00	87.07	116.81	0.532	2.27	0.51
	fibre libriform, µm	20	23.80	19.73	26.48	0.125	2.35	0.53

DISCUSSION

The issues of the structure and properties of wood of some tree species and their roots were first dealt with by Chernyaev (1864), who described the structure of the middle part of pine (*Pinus sylvestris* L.) root. But most part of his work was engaged in studying only the middle part of roots of coniferous species.

The results of our studies on the macroscopic structure of SRW and SW show that the transition from SW to root wood is rather smooth and there is much in common in their structure. In the cross section of perennial roots of pine (*Pinus sylves-*

tris L.), spruce (*Picea abies* Karst.) and fir (*Abies alba*), the same alternation of annual layers of early and late wood can be seen, as well as in the trunks.

The sharply marked boundary between the trunk and the root is not easy to find, as the tissues of the trunk gradually pass into the tissues of the root. The structure of the wood of large perennial roots has much in common with the structure of the wood of the trunk, as Ugolev (1986) noted in his work.

Since the main function of large roots is to conduct water, their wood is dominated by wide-cavity thin-walled elements, which give them a porous structure, as noted in the works of Guz (1996), Kalinin (1983) and Kalinin et al. (1998). It is also described that the boundary between the annual layers is not very noticeable, and the transition from early to late wood is smoother. This is due to the lack of sharp seasonal fluctuations in temperature and humidity of the environment and moisture content in the soil. But nothing is said in their works about comparison of the internal structure of the SRW and SW. Vikhrov (1953) in his comparative studies noted that the annual layering becomes less pronounced with distance from the root collar. Tracheids in the secondary wood of the root, as well as in the wood of the trunk, are arranged in regular radial rows. They contain bordered pores from one to three rows [in pine (*Pinus sylvestris* L.), spruce (*Picea abies* Karst.), fir (*Abies alba*)]. Bordered pores are often found on the tangential walls of the late and early tracheids (except juniper). This feature of the structure reflects the great adaptation of the root wood to perform the water supply function.

The alternation of annual layers is also observed in birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.), the wood of their roots being dominated by vessels and libriform fibres. The annual layers of the roots differ from the annual layers of the trunk in their uneven development and indistinct boundaries. The annual layers are harder to count in the roots than in the trunk since they are poorly distinguished there.

The study of Tumanyan (1953) showed that in some hardwoods, vessels in the wood of the roots are strongly developed, the annual layers are narrow and poorly visible, and there is almost no difference between early and late wood. In particular, the wood of the roots of hardwooded broadleaved species contains a large amount of woody parenchyma, and it is present in higher amounts there than in the trunk.

The roots of coniferous and broadleaved species under study do not have a permanent type of eccentricity. One and the same root of pine (*Pinus sylvestris* L.), even in a relatively small area, can develop eccentrically in different directions (Fig. 2).

The peculiarities of the microstructure lie in the fact that, in terms of the cross-sectional shape, the early tracheids in the SRW of coniferous species can take very different shapes – from square, rectangular to polygonal – while in the SW of fir (*Abies alba*), they are polygonal,

Figure 2. Peeled stumps of pine (*Pinus sylvestris* L.)

and in spruce (*Picea abies* Karst.) and pine (*Pinus sylvestris* L.), they are of a rectangular shape with a much larger side in the radial direction. The late tracheids of this wood have almost the same shape. They are somewhat compressed in the radial direction and elongated in the tangential direction (Fig. 3). Early SRW tracheids, as evidenced by the data in Table 2, have thinner walls (by 19–28%) and a larger internal cavity (by 15–25%) compared to similar SW elements (Fig. 4). However, there is no significant difference between the late tracheids of these types of wood: the walls are very thick and the internal cavities are small; within one growth layer, the transition of early tracheids to late ones is gradual.

The thickness of the tracheid shell of pine (*Pinus sylvestris* L.) roots during the transition to the late zone first increases to a maximum and then decreases again near the border of the annual ring. Manwiler (1972), during his study of the southern pine (*Pinus pinaster* Ait.), found that the tracheids of the roots were one third longer and one third larger in diameter, their walls were 18% thinner and the gaps were almost two thirds larger than the tree trunk tracheids measured at stump height. The tracheids of horizontal roots were longer and had thicker walls than those of the roots of other orientations; length, cell diameter and gap diameter increased along the root. In non-horizontal roots, the diameter of cells and gaps decreased, while the length

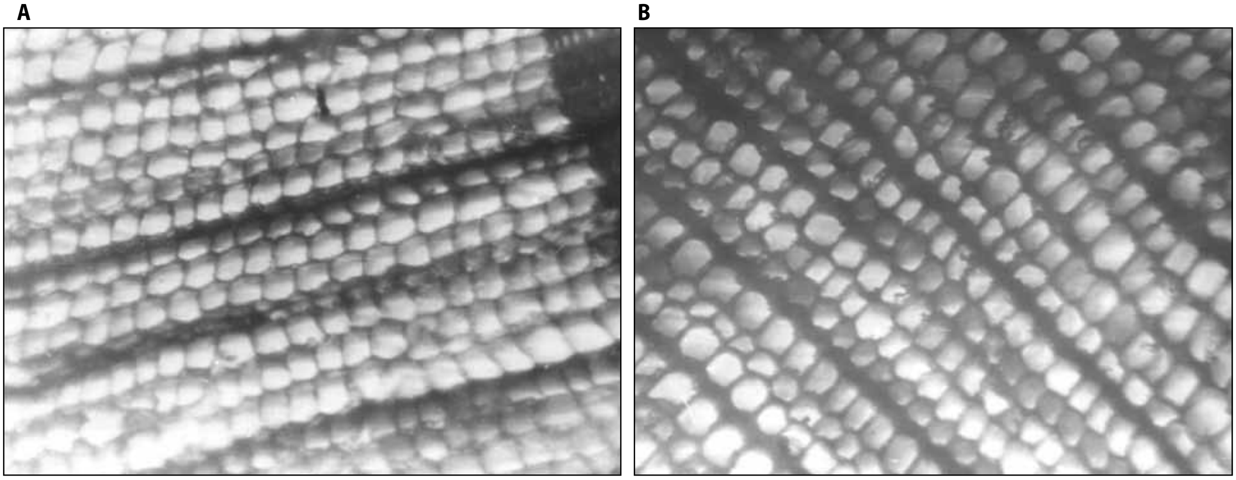

Figure 3. Forms of tracheids on the cross section of stump-root wood (A) and stemwood (B) of fir (*Abies alba*) (140×)

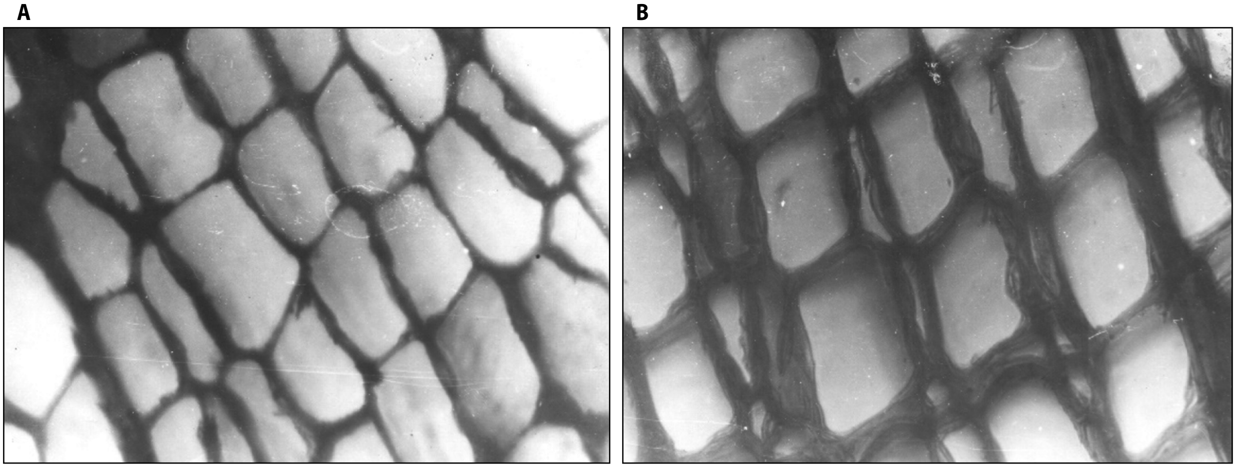

Figure 4. Forms of tracheids in the cross section of stump-root wood (A) and stemwood (B) of pine (*Pinus sylvestris* L.) (420×)

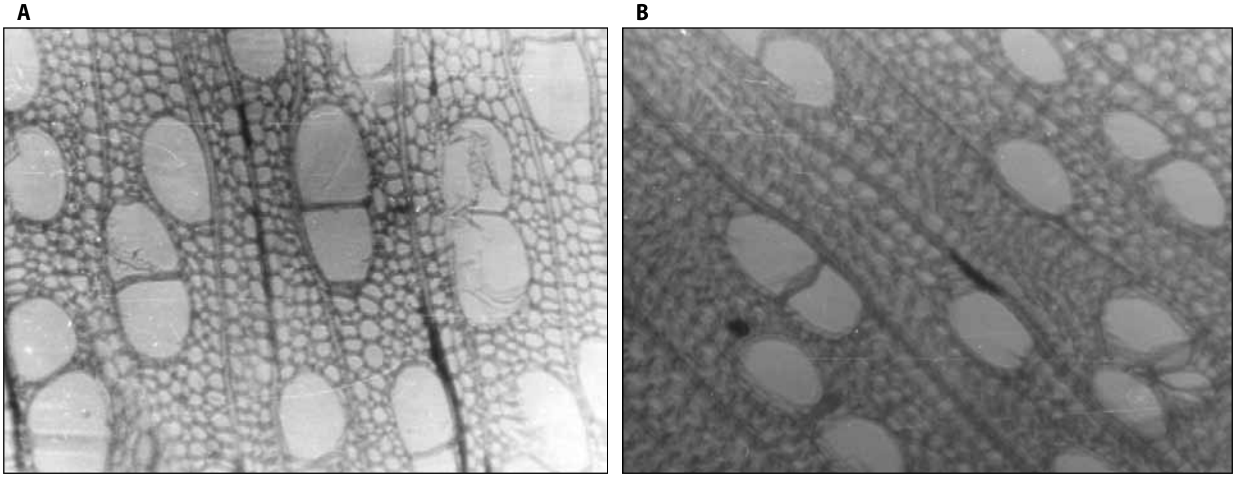

Figure 5. Cross section of stump-root wood (A) and stemwood (B) of aspen (*Populus tremula* L.) (140×)

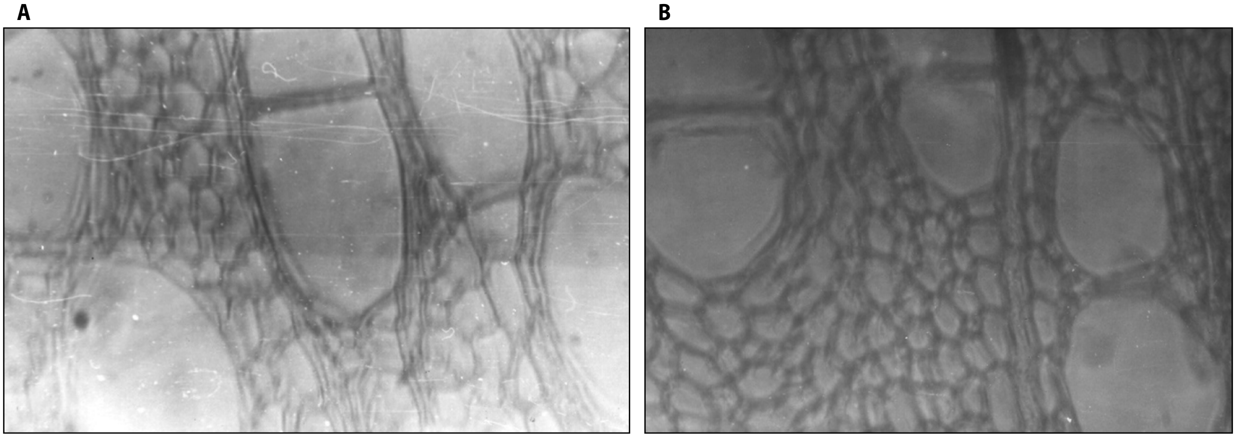

Figure 6. Cross section of stump-root wood (A) and stemwood (B) of birch (*Betula pendula* Roth.) (280×)

and thickness of the wall increased. Along the taproot, all dimensions increased to a maximum and then they decreased. His research was concerned with only one species of pine (*Pinus sylvestris* L.). In spruce (*Picea abies* Karst.) and fir (*Abies alba*), large, developed roots have fairly wide tracheids with thicker walls than in pine (*Pinus sylvestris* L.) roots but are smaller in size than in SW.

The study of the microstructure of hardwoods emphasises that the wood of aspen (*Populus tremula* L.) roots (Fig. 5) and that of birch (*Betula pendula* Roth.) (Fig. 6) differs little in structure from SW. Being representatives of diffuse-porous species, all vessels in their wood are small, relatively evenly scattered on the annual ring and, in some places, several pieces are located together, forming radial or tangential groupings.

The bulk of the cells of all hardwoods consists of libriform fibres. On the cross section of the root wood, the libriform has the appearance of predominantly rounded cells with narrow cavities and thick walls, and on the microsections of the SW, the libriform fibres are characterised by mostly angular cells with gaps and thick walls.

Thus, the results of macro- and microscopic studies show that there are differences in internal structure between the SRW and the SW. The wood of the roots is dominated by large, wide-cavity, thin-walled elements that give it a porous and brittle structure, which is less pronounced in the wood of the trunk.

CONCLUSIONS

The results of comparative studies of SRW and SW allowed us to draw the following conclusions:

1. It is established that in the structure of wood with perennial roots, mostly the same structural elements are present as in the SW. But, along with this, there are many differences, although it is impossible to indicate a sharp border between them, as their tissues gradually merge into one another.
2. It was found that the main features of the macrostructure of the roots were the uneven development of annual layers and fuzziness of their boundaries, absence of a constant type of eccentricity and a sharp transition from early to late wood.
3. It was found that in all species, the width of the annual rings in the SRW was greater than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 84.62%; in spruce (*Picea abies* Karst.) – by 73.68%; in fir (*Abies alba*) – by 93.75%; in aspen (*Populus tremula* L.) – by 35.71% and in birch (*Betula pendula* Roth.) – by 105.0%. It is established that the content of late wood in the SRW of conifers is lower than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 19.60%; in spruce (*Picea abies* Karst.) – by 27.30% and in fir (*Abies alba*) – by 21.69%, which is primarily due to the leading function of the stump-root systems of trees.
4. It is estimated that in all species, the number of annual rings per 1 cm in the SRW is less than in the SW, in particular, in pine (*Pinus sylvestris* L.) – by 46.05%; in spruce (*Picea abies* Karst.) – by 42.31%; in fir (*Abies alba*) – by 47.54%; in aspen (*Populus tremula* L.) – by 27.78% and in birch (*Betula pendula* Roth.) – by 52.00%.
5. Differences in the microscopic structure between the SRW and SW are revealed, which consist in the difference in sizes of the main constituent elements: tracheids in conifers and vessels and libriform fibres in hardwoods.
6. It was found that in all coniferous species, the transverse dimensions of early tracheids in the SRW were greater than in SW, in particular, in the radial direction in pine (*Pinus sylvestris* L.) – by 32.78% and in spruce (*Picea abies* Karst.) – by 18.67%; in fir (*Abies alba*) – by 22.54%; in the tangential direction near pine (*Pinus sylvestris* L.) – by 8.03%; in spruce (*Picea abies* Karst.) – by 1.21% and in fir (*Abies alba*) – by 14.92%. Regarding the late tracheids, we obtained the following results: in the radial direction, there was an increase in pine (*Pinus sylvestris* L.) – by 14.45% and in fir (*Abies alba*) – by 7.98%; in spruce (*Picea abies* Karst.), there was a decrease by 17.82%; and in the tangential direction, there was a decrease in all species: in pine (*Pinus sylvestris* L.) – by 15.30%; in spruce (*Picea abies* Karst.) – by 4.01% and in fir (*Abies alba*) – by 5.32%.
7. It is established that, in terms of the cross-sectional shape, the early tracheids in the SRW of coniferous species can take very different shapes – from square, rectangular to polygonal, while in the SW of fir (*Abies alba*), they are polygonal, and in spruce (*Picea abies* Karst.) and pine (*Pinus sylvestris* L.), they are of a rectangular shape with a much larger side in the radial direction. The late tracheids of this wood have almost the same shape. They are somewhat compressed in the radial direction and elongated in the tangential direction. The interval of the sizes of early and late tracheids both in root wood and in the SW in the radial direction is approximately 1.5–2.5.
8. It is established that the thickness of the walls of early and late tracheids in the SRW of coniferous species is less than that of SW in all species, in particular, in pine (*Pinus sylvestris* L.) – by 23.81% for early tracheids and by 13.64% for late ones; in spruce (*Picea abies* Karst.) – by 19.35% and 24.00%, respectively, and in fir (*Abies alba*) – by 27.78% and 12.20%, respectively.
9. It was found that in broadleaved species, the diameters of vessels and libriform fibres in the SRW were larger than in SW, in particular, in aspen (*Populus tremula* L.) – by 20.41% for vessels and by 12.95% for libriform fibres and in birch (*Betula pendula* Roth.) – by 20.69% for vessels and by 18.41% for libriform fibres.

References

Chavchavadze, E.S. 1979. Coniferous wood (in Russian). Nauka, Leningrad.

Chernyaev, P.O. 1864. On the structure of the middle part in the roots of arboreal dicotyledonous plants (in Russian). *Natural History Research*, 1, 130.

Gayda, S.V. 2013. Bases of secondary wood resources classifier formation (in Ukrainian with English summary). *Proceedings of the Forest Academy of Sciences of Ukraine*, 11, 208–215.

Gayda, S.V. 2016. A investigation of form of stability of variously designed blockboards made of post-consumer wood. *ProLigno: Scientific Journal*, 12 (1), 22–31.

Gayda, S.V., Kiyko, O.A. 2020. Determining the regime parameters for the surface cleaning of post-consumer wood by a needle milling tool. *Eastern-European Journal of Enterprise Technologies*, 5 (1 (107)), 89–97. DOI: 10.15587/1729-4061.2020.212484

Gayda, S.V., Kiyko, O.A. 2020. The investigation of properties of blockboards made of post-consumer wood. *Drewno. Prace naukowe. Doniesienia. Komunikaty*, 63 (206), 77–102. DOI: 10.12841/wood.1644-3985.352.10

Gayda, S.V., Kiyko, O.A. 2021. Post-consumer wood properties as an important factor in the quality of constructional materials (in Ukrainian with English summary). *Proceedings of the Forest Academy of Sciences of Ukraine*, 23, 152–162. DOI: 10.15421/412135

Geles, I.S. 1978. Physicochemical studies of wood and its complex use (in Russian). Karelian branch of the USSR Academy of Sciences, Petrozavodsk.

GOST 16483.0:1989. 1989. Wood. General requirements for physical and mechanical tests (in Russian). Gosstandart, Moscow.

GOST 16483.6:1980. 1980. Wood. Method of selection of model trees and logs for determination of physical and mechanical properties of wood plantations (in Russian). Gosstandart, Moscow.

GOST 16483.18:1972. 1972. Wood. Method for determination the number of annual rings in 1 cm and content of latewood in an annual ring (in Russian). Gosstandart, Moscow.

Guz, M.M. 1996. Root systems of tree species of the Right-bank forest-steppe of Ukraine (in Ukrainian).

Hakkila, P. 1976. Stumpwood as industrial raw material (in Finnish with English summary). *Folia Forestalia*, 292, 1–39.

Howard, E.T. 1974. Slash pine rootwood in flakeboard. *Forest Products Journal*, 24 (6), 29–35.

ISO 3129:2019. 2019. Wood – Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens.

Kalinin, M.I. 1983. Formation of tree root systems (in Russian). Timber industry, Moscow.

Kalinin, M.I., Guz, M.M., Debrinyuk, Y.M. 1998. Forest root science (in Ukrainian). Institute of content and teaching methods, Lviv.

Manwiller, F.G. 1972. Tracheid dimensions in rootwood of southern pine. *Wood Science*, 5 (2), 122–124.

Mutovina, M.G. et al. 1983. Production of fibrous semi-finished products from the entire biomass of deciduous trees (in Russian). *Paper Industry*, 7, 5–6.

Nikishov, V.D. 1985. Integrated use of wood (in Russian). Forest Industry, Moscow.

Nikityuk, L.O., Gayda, S.V., Guz, M.M. 1993. Prospects for the production of chipboard from stump-root wood (in Ukrainian). *Forest Journal*, 3, 29.

Nikityuk, L.O., Gayda, S.V., Guz, M.M., Plys, L.S. 1993. Stocks of stump-root wood – an additional resource of raw materials (in Ukrainian). *Ukrainian Forest*, 2, 10–12.

Perelygin, L.M. 1954. Wood structure (in Russian). Publishing house of the USSR Academy of Sciences, Moscow.

Pyslar, G.I. 1936. Anatomical structure of the root of the main branches of fruit trees (in Russian). *Proceedings of the Institute of the Moldavian Agricultural Institute*, 1, 56–69.

Ratajczak, E. 2013. Sektor leśno-drzewny w zielonej gospodarce (in Polish). Wydawnictwo Instytutu Technologii Drewna, Poznań, 62–69.

Ratajczak, E., Szostak, A., Bidzinska, G., Leszczyszyn, E. 2018. Market in wood by-products in poland and their flows in the wood sector. *Drewno. Prace naukowe. Doniesienia. Komunikaty*, 61 (202), 5–20.

Tumanyan, S.A. 1953. Comparative anatomical structures of wood (in Russian). *Proceedings of the Forest Institute of the USSR Academy of Sciences*, 9, 212.

Ugolev, B.N. 1986. Wood science with the basics of forest commodity science (in Russian). Timber Industry, Moscow.

Vikhrov, V.E. 1953. Diagnostic signs of wood (in Russian). Publishing house of the Academy of Sciences of the USSR, Moscow.

Vintonov, I.S., Sopushinskyy, I.M., Taishinger, A. 2007. Wood Science (in Ukrainian with English summary). Priority, Lviv.

Wheeler, E.A. Baas, P., Gasson, P.E. 1989. IAWA of microscopic features for hardwood identification. *IAWA Bulletin*, 10 (3), 221–332.

Yatsenko-Khmelevskyy, A.A 1954. Fundamentals and methods of anatomical research of wood (in Russian). USSR Academy of Sciences, Moscow.