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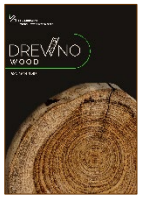

Interspecies Interactions in Dual Cultures of Selected Fungi Species and Their Influence on The Decomposition of Scots Pine and Norway Spruce Wood Substrates

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Wood is a material that is used in many sectors of the economy, including the furniture industry and lumbering. After felling, trees are processed into appropriate sorts and transported to forestry landings. Wood substrate stored in forestry landings provides an excellent food base for fungi. The decomposition of wood by fungi leads to a decrease in the quality of the raw wood material. Therefore, research was carried out using selected cultures of fungi isolated from fruiting bodies found on pine and spruce logs collected at a landing. For this purpose, the growth of the mycelium of 10 fungi was tested in single and dual cultures. The effect of fungi on the intensity of decomposition of sawdust substrates from the sapwood and heartwood of Scots pine and Norway spruce was also examined. The results showed that fungal cultures grow at different intensities, reaching diameters that range from a minimum of 30.0 mm (as for Sparassis crispa) to a maximum of 90.0 mm (as for Phlebiopsis gigantea, Heterobasidion annosum and Phaeolus schweinitzii). The development of fungi in dual cultures showed that the cultures interact with each other in an antagonistic manner. An experiment on the decomposition of sawdust by fungi showed that its intensity depends on the sawdust type, the tree species, and the enzymatic capacity of the fungi.

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Introduction

Forestry plays a very important role both in the life of society and in the Polish economy. The general area of forest management includes a wide range of specialized tasks aimed at maintaining and increasing forest resources and ensuring their protection [Korcyl and Czajka 2011; Sierota et al. 2019]. Among the main principles of rational forest management is the production of wood and of appropriate assortments from it, such as wood logs and piles [Forests Act of 28 September 1991, Dz.U. (Journal of Laws) 2022, No. 672]. Wood assortments are a basic raw material produced for use in many industries, such as lumbering, furniture manufacture, the cellulose and paper industries, and heating [Domagała and Sztabińska 2021]. Tree

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species whose wood is ideal for producing various types of assortments include Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.). Among the most important properties of pine and spruce wood are their resistance to mechanical damage, elasticity, and ease of machine processing. Therefore, the wood of these species is commonly used in the construction and furniture industries, which are important strategic industries in Poland. To enable wood to be collected efficiently, the harvested raw wood material is transported and stored at landings. Forest landings are places adapted to store wood, which are distributed throughout the area administered by a forest inspectorate [Domagała and Sztabińska 2021]. Raw wood material can be stored at landings for periods ranging from several days to a number of weeks. Unfortunately, both the health condition of living trees and the quality of their wood, when stored at landings for a longer period of time under changing atmospheric conditions such as precipitation and temperature, may deteriorate due to endophytic and rot fungi [Kwaśna et al. 2016].

Endophytes are fungi that are able to colonize plant tissues in an asymptomatic manner in a very short period of time [Arnold 2007; Boddy 2001; Schulz and Boyle 2005; Song et al. 2017]. The rate of colonization of the food substrate by endophytes is influenced by the optimal development conditions for their growth. The basic conditions that induce the growth of endophytes include high humidity of the food substrate (at least 80.0%), location of the food substrate in semi-shaded conditions, and the lack of air circulation, e.g. wind. Ideal locations, offering conditions that stimulate the intensive development of endophytic fungi, are landings where raw wood material is stored. Wood stored at high humidity without direct access to sunlight provides an ideal food substrate for endophyte colonies. Endophytes have a wide range of food preferences. These fungi can colonize plant tissues and develop inside them, remaining harmless to the plant and not causing any disease symptoms such as changes in the colour and structure of the wood or more expansive and harmful saprotrophs or pathogens. As a result of the growth and development of endophyte hyphae, the structure of plant cells can become weaker, making them susceptible to other infections from macrofungal species [Arnold 2007; Bacon and White 2000; Boddy and Griffith 1989; Schulz and Boyle 2005]. Undoubtedly, fungal endophytes facilitate fungal rot infections and the colonization of wood; however, rot-causing fungi have also found other ways to effectively colonize raw wood material. Pathways for infection and colonization of wood cells by rot fungi include necrosis occurring within sapwood, the presence of wounds in heartwood, dead branches of living trees, and edge cracks and end cracks of harvested wood [Kwaśna et al. 2016]. Rot-causing fungi include species that are dangerous pathogens (necrotrophs), attacking only healthy trees, as well as saprotrophs that colonize and decompose mainly dead wood [Hulcr and Dunn 2011; Sołtys and Zawadzki 2018]. Rot fungi can cause white, brown or white pocket rot. Fungal species causing white wood rot have the ability to enzymatically decompose wood components such as lignin, cellulose and hemicellulose, leading to complete decomposition of the wood structure [Osmenda and Nawrot-Chorabik 2024]. An example of a fungus species that causes intensive decay of wood from coniferous trees, such as pine and spruce, is *Phanerochaete carnosa* (Burt. Parmasto) [El-Nasser et al. 1997; Goodell et al. 2008; Suzaki et al. 2012]. In contrast, the fungi causing brown rot have the ability to decompose only cellulose, causing the wood to take on a dark brown colour and a brittle structure. Fungi that cause brown rot include, among others, *Gloeophyllum trabeum* ((Pers.) Murrill), which colonizes and decomposes wood of both coniferous and deciduous trees [D'Souza et al. 1996]. The last type of rot to consider is white pocket rot. Fungi causing this type of wood decomposition have the ability to enzymatically decompose all wood components (cellulose and lignin), giving the characteristic symptoms of wood infestation, namely red discoloration with evenly distributed pockets in which, as a result of the enzymatic action of fungal pathogens, lignin has been decomposed and traces of cellulose proteins remain. An example of a fungus that causes this type of wood decay is *Heterobasidion abietinum* (Niemelä and Korhonen), which causes serious damage in spruce stands [Garbelotto and Gonthier 2013; Goodell et al. 2008; Szewczyk 2015].

Rot fungi and endophytes contribute to the progressive decomposition of wood. However, the rate and amount of decomposed raw wood material may vary due to the fungus' food preferences and the speed of its culture development. Nevertheless, it should be emphasized that raw wood material is a habitat and food substrate colonized by many fungal species. This is important to note, because different species of fungi can interact with each other. An example of the interaction of fungal cultures is the production by their growing mycelia of metabolites that stimulate or restrict the development of fungal cultures growing in the same food base but not belonging to the same species. The ability of fungi to intensively decompose wood, especially that of economically valuable tree species such as Scots pine and Norway spruce, results in deterioration of its quality and durability [Czajka and Kaczka 2002; Šilinskas et al. 2020; Tomczak et al. 2010]. The end result of the presence of fungi is reduced usability of the raw material in industries such as furniture or lumbering.

The following study presents the effects of interspecies fungal interactions affecting the growth and

development of various fungal cultures developing on the wood of Scots pine and Norway spruce. This is a very important problem, as the decomposition of raw wood material due to fungi has a highly negative effect on pine and spruce wood, which offer valuable properties. In order to carry out this study, fungus–fungus type dual cultures growing on PDA agar–glucose–potato medium were used. Also investigated was the intensity of the decomposition of the food substrate, namely sapwood and heartwood sawdust from pine and spruce, by selected fungi. The fungal species studied were *Phlebiopsis gigantea* ((Fr.) Jülich), *Heterobasidion annosum* ((Fr.) Bref.), *Postia ptychogaster* ((F. Ludw.) Vesterh.), *Porodaedalea pini* ((Brot.) Murrill), *Phaeolus schweinitzii* ((Fr.) Pat.), *Sparassis crispa* ((Wulf.) Fr.), *Byssomerulius corium* ((Pers.) Parmasto), *Conferticium ochraceum* ((Fr.) Hallenb.), *Clonostachys* sp. and *Fomitopsis pinicola* ((Sw.) P. Karst.) [Aguadé et al. 2015; Gramss 2020; Hagle and Filip 2010; Kakeya at al. 2002; Larson and Larson 2003; Mukrimin et al. 2019; Ohno et al. 2002; Stalpers et al. 2021; Szewczyk 2013; Zmitrovich et al. 2006; Żółciak et al. 2020].

The characteristics of the fungi species isolated from wood fragments of Scots pine and Norway spruce are presented in Table 1.

The results of this research may contribute to the development of innovative methods for protecting pine and spruce wood stored in forest landings against the negative and expansive impact of fungi having the ability to intensively decompose raw wood material. This assumption is confirmed by research concerning the use of a substance derived from fungi, chitosan, to combat dangerous parasitic fungi on plant roots, such as *Fusarium oxysporum* (Schltdl) [Palma-Guerrero et al. 2008]. The research also included determination of the degree of harmful impact of selected fungi species on the processed wood raw material, namely pine and spruce sawdust. The results obtained will be used to develop effective methods for securing and protecting crushed wood raw materials such as chips and sawdust stored at forest landings and sawmills. This is a very important goal, because fungi, through their colonization of processed raw wood, cause its destruction and deterioration of its quality, which prevents the use of sawdust and chips in the heating industry and for the production of pellets.

Materials and methods

1. Research material

Fungal cultures were collected from fragments of pine and spruce wood on which the fruiting bodies of fungus species selected for study were observed. The wood fragments exhibited visible symptoms of disease, such as visible rot and discoloration. Logs with visible fungi fruiting bodies were stored in landings located in Spała and Garwolin Forest Districts. The samples of wood containing the fungi cultures were taken from the middle part of the logs. The analyses were carried out at the Department of Forest Ecosystem Protection of the University of Agriculture in Kraków, Poland. Fungi were isolated by disinfecting the wood fragments with 96.0% ethanol and drying them with absorption paper. Each of the collected samples was placed in a Petri dish with solidified PDA+T medium (potato dextrose agar, Biocop, 200 mg/L tetracycline) prepared according to the recommendations of TZF Polfa, Poland. The samples were incubated in a Heraeus incubator (model BK600, Burladingen, Germany) for seven days in total darkness. Then, the fungal inocula grown from the samples were collected and subjected to genetic analysis by PCR to identify the fungus species.

The mycelia fragments were placed in 2 ml Eppendorf-type tubes. DNA extraction of individual fungi was performed using a Genomic Mini AX. The procedure was carried out according to the instructions of the manufacturer A&A Biotechnology (Gdynia, Poland). PCR analysis of the ITS region (ITSI-5.8SITS2) was also performed using ITS4 and ITS5 [White et al. 1990], and a gene fragment amplification procedure was performed using Big Dye Terminator v3.1 Cycle Sequencing (Applied Biosystems, Forest City, CA, USA). Subsequently, the obtained DNA sequences were verified using the Chromas Pro 1.6 software (Technelysium, Australia) and compared through the NCBI GenBank database, using the BLAST tool for finding the most similar gene sequences for each species.

Data from the NCBI GenBank database for fungal species isolated from wood fragments of Scots pine and Norway spruce are presented in Table 1.

2. Preparation of test substrates

First, selected substrates were prepared on which the fungi would grow during the experiments. The first PDA (potato dextrose agar) medium was prepared according to the instructions of the manufacturer Biocorp (Poland). Substrates in the form of sapwood or heartwood sawdust made of healthy wood fragments (discs) of Scots pine and Norway spruce wood were also prepared for the study. This research represents an original method of assessing the possibility of decomposition by rot fungi of shredded wood substrate, including wood chips and sawdust, which are used in the wood industry to produce pellets and briquettes. Fragments of wooden blocks were not used in the experiments, because the solid structure of wood does not reflect the structure of processed wood such as sawdust and chips.

Table 1. Characteristics of selected fungal species isolated from Scots pine and Norway spruce wood

Fungal species	A type of nutrition	A type of rot caused by the fungus	The species of wood from which the fungus was isolated	Fungi numbers according to the NCBI genetic database
Phlebiopsis gigantea	Saprotroph	White rot	Scots pine	MF475979.1
Heterobasidion annosum	Pathogen	White pocket rot		KC492913.1
Postia ptychogaster	Saprotroph	Brown rot		JF950576.1
Porodaedalea pini	Pathogen	Red ring rot		HE971113.1
Phaeolus schweinitzii	Pathogen	Brown rot		FR686570.1
Sparassis crispa	Pathogen/Saprotroph	Brown rot		JX566465.1
Byssomerulius corium	Saprotroph	White rot	Norway spruce	KF856504.1
Conferticium ochraceum	Saprotroph	White rot		KT943933.1
Clonostachys sp.	Endophyte	lack		AJ876484.1
Fomitopsis pinicola	Pathogen/Saprotroph	Brown rot		KC595922.1

The study reflects the real possibilities of decomposition of wood biomass by fungal species that have the ability to colonize and decompose shredded wood.

For the preparation of sawdust, fragments of pine and spruce wood were taken from healthy trees. The trees from which wood discs were taken to prepare sawdust were 85 years old. Wooden discs of pine (disc diameter 300.0 mm) and spruce (disc diameter 280.0 mm) were taken from the middle part of the tree trunk using a Husqvarna chainsaw (model 365 X-Torq, Warsaw, Poland). The heartwood radius of the pine was 120.0 mm, and the remaining part of the pine wood disc was sapwood. In the case of spruce, the radius of the heartwood was 100.0 mm, the remaining part of the disc being sapwood. The radii of both wooden discs were measured from a clearly visible core. Each wooden disc was cut in half to provide easy access to the specific types of wood (sapwood and heartwood).

Then, each of the wood discs was chopped using a Dedra 2000 circular saw (Dedra Exim, Pruszków, Poland) equipped with a Verto circular blade (ndiUnimet, Rzeszów, Poland). The sawdust obtained was divided into two batches, sapwood and heartwood sawdust, separately for Scots pine and Norway spruce. Then each batch of sawdust was sifted through a sieve with a mesh size of 0.8 mm. The sifted batches of sawdust were divided into single portions each weighing 0.4 g. Each individual portion of sapwood or heartwood sawdust constituted a single test sample. Then each portion of sawdust was sterilized in a Bidner Model E 28 laboratory dryer at a temperature of 90 °C for 8 hours. During the sterilization of the sawdust, Petri dishes were prepared with the previously prepared PDA medium. A circular hole of size 30.0 mm was cut out in the solidified medium with a punch, into which separately sterilized sapwood and heartwood sawdust obtained from pine and spruce wood were placed. Sterile wood substrate was evenly distributed in the center of the Petri dish and gently pressed with a sterile scalpel to reduce the size of air spaces between the sawdust fragments. The sawdust was then moistened with 500 µl of sterile distilled water. Then in the laboratory, using a sterile moisture meter (Benetech Poland model GM620, Kalisz, Poland), sawdust moisture was measured. The moisture content of both pine and spruce sawdust was approximately 13% (Fig. 1C: 7–10). There were 24 Petri dishes each filled with sapwood and heartwood sawdust (a total of 48 pine sawdust samples were obtained, with a substrate weight of 19.2 g). The possibility of decomposition of pine sapwood and heartwood sawdust was examined using cultures of six species of fungi. There were also 16 Petri dishes filled with sapwood and heartwood sawdust made from spruce wood (a total of 32 samples of spruce sawdust were obtained with a substrate weight of 12.8 g). The possibility of decomposition of spruce sapwood and heartwood sawdust was examined using cultures of four species of fungi.

3. Growth of selected fungi in single cultures

A 10 mm diameter disc-shaped inoculum was taken from the previously propagated fungal cultures. The inoculum of each fungal species was then placed onto solidified PDA medium located in a Petri dish. Each inoculum was placed in the centre of the Petri dish. After lining with the inoculum of each fungal species, the dishes containing the test material were secured with parafilm (Fig. 1A: 1–3). Fungal cultures isolated from pine wood were grown on 24 Petri dishes, and fungal cultures isolated from spruce wood on 16 Petri dishes. The experiment lasted for 21 days.

4. Determination of interspecies fungal interactions using dual cultures and a method of measuring the size of fungal cultures

The dual cultures were samples placed on the PDA medium. Two different cultures of selected fungal species were placed in a single Petri dish. The inoculum of each fungal species had the shape of a 10.0 mm disc. The inocula of different species were placed collaterally on the nutrient substrate at a distance of 10.0 mm. The fungal cultures were labelled as a test culture (TC) and a tester (T). The test culture was defined as the inoculum of the fungus species whose growth potential was to be tested by exposure to a fungus of another test species. The fungus referred to as the tester was the fungus species that grew in the presence of the test culture. Each species was tested against every other to determine its effect on the growth of other fungi (Fig. 1B: 4–6). The fungal cultures growing on PDA medium placed in Petri dishes were secured and placed in a Heraeus model BK 600 incubator (Burladingen, Germany) at approximately 22 °C. A total of 120 combinations of dual cultures were obtained for fungi isolated from pine wood, and 48 combinations for dual cultures isolated from spruce wood. The experiment lasted for 21 days.

After the period of the experiment, the single and dual cultures were measured linearly, i.e. along the longer edge of the developed mycelium, so that the sizes of the cultures were stated in millimetres. The method for measuring dual cultures of fungi is shown in Figure 2.

4. Dry sapwood and heartwood – sawdust loss due to fungi

Inoculum discs, 10.0 mm in size, of each fungal species were collected from previously grown fungal cultures. Each inoculum was placed individually on sawdust located in the Petri dishes. The fungal cultures isolated from pine wood were placed on pine sapwood and heartwood sawdust, and those isolated from spruce wood on spruce sapwood and heartwood sawdust (Fig. 1C: 11–12). The single fungal cultures grew on sawdust for 45 days. At the end of the experiment, each sample of pine and spruce sapwood and heartwood sawdust, on which only fungi had developed without any remnants of the agar medium, was transferred from the Petri dishes to individual aluminium bags, which had heat-conducting properties, without damaging the test material (sawdust). The sealed bags containing the sawdust were placed in a Bidner Model E 28 laboratory dryer at 90 °C for 8 hours to remove fungal hyphae from the sawdust. After the drying process, it was checked whether all remnants of the mycelium of the tested fungi had been removed. It was found that after drying of both pine and spruce sawdust, no fungal hyphae remained. The dried sawdust samples were then dampened using an Explorer Analytical digital balance (OHAUS Europe, Nanikon, Switzerland). The dry matter loss of pine and spruce sapwood and heartwood sawdust was assessed based on the difference in the average amount of the sawdust mass before and after the experiment, i.e. after 45 days. The average weight of sapwood and heartwood sawdust was the average weight calculated on the basis of sawdust weight measurements of individual samples for each fungus species.

5. Statistical analyses

The data obtained from the experiments were statistically analysed using Dell Statistica version 13.1 [Dell Inc. 2016]. Statistical analyses were carried out using RIR tests to determine normality of means distribution, and post hoc Tukey multiple comparisons of means to determine the growth potential and development of single and dual cultures of fungi. The assessment of the growth and development of fungi collected in single cultures was made by comparing the size of fungal cultures separately for fungi inhabiting pine and spruce wood. In the case of dual cultures of fungi, the assessment of the growth and development of individual cultures was made based on assessment of the relationship between the tested culture (TC) and the tester (T). An analysis was also performed using the t-Student test, comparing the mean in two groups while determining the variance of the studied groups, in order to determine the amount of decomposition of the sapwood and heartwood substrate caused by the growth of cultures of selected fungal species. The last statistical test carried out was a non-parametric Kruskal–Wallis analysis of variance, complemented by the HSD Tukey test to determine which fungal species caused the greatest average decomposition of the tested pine and spruce sawdust samples. The tests were performed assuming a significance level of $p < 0.05$.

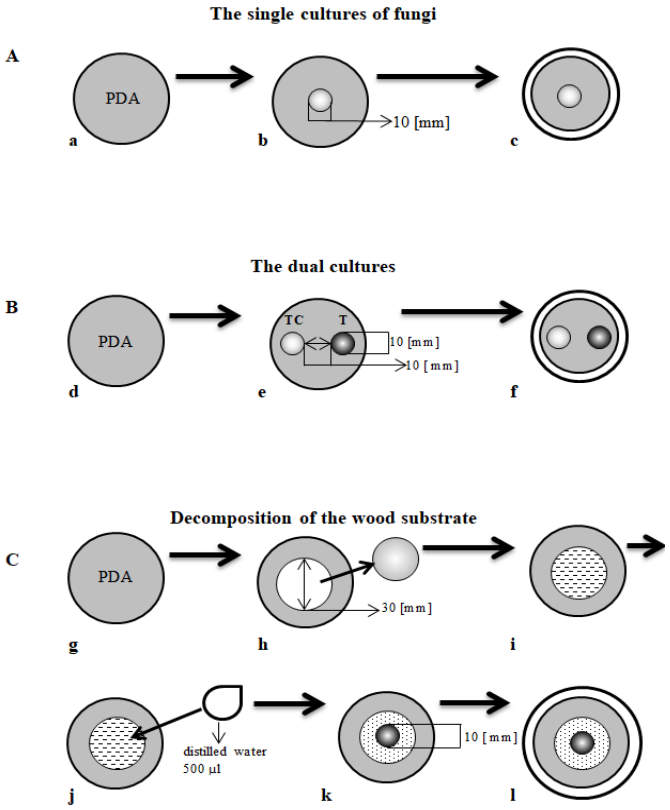

Fig. 1. Successive stages of the experiments. The order of the stages is indicated by bold arrows

A: a – Filling a Petri dish with solidified PDA medium (potato dextrose agar), b – Placing a fungal inoculum with a diameter of 10.0 mm in the centre of the dish with PDA medium, c – Closing and securing the dish with fungal cultures.

B: d – Filling the Petri dish with solidified PDA medium (potato dextrose agar), e – Placing inoculum of different fungal species in the dish with PDA medium. The inoculum of each fungal species had a diameter of 10.0 mm. The fungi were marked as a test culture (TC) and a tester (T) and placed at a distance of 10.0 mm, f – Closing and securing the Petri dish with dual fungal cultures.

C: g – Filling the Petri dish with solidified PDA medium (potato dextrose agar), h – Cutting out the disc in the PDA medium with a die and removing it (grey circle in the illustration). A hole is left in the medium with a diameter of 30.0 mm, i – Placing the sawdust in the cut hole (in each Petri dish of pine or spruce sapwood or heartwood), distributing it evenly and pressing with a sterile scalpel, j – Moistening the sawdust with 500 µl of distilled water and measurement of sawdust moisture using a moisture meter, k – Placing a fungal inoculum with a diameter of 10.0 mm on the sawdust, l – Closing and securing the Petri dish with inoculum of a given fungal species.

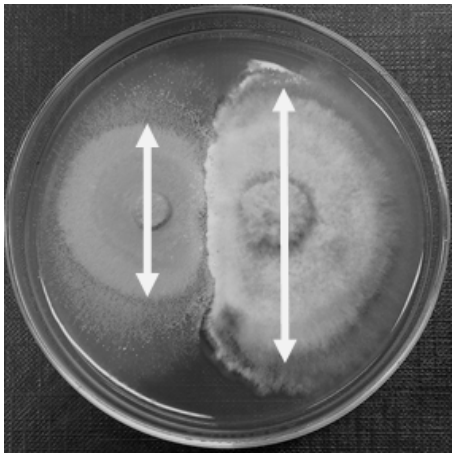

Fig. 2. Measurement of the size of the test culture (left), here *P. ptychogaster*, and the tester (right), here *P. pini*. The white arrow indicates the direction of the linear measurement

Results and discussion

The experiments carried out in this study showed the variability of the fungal growth rates, the interactions that occurred between cultures of different fungal species, and their abilities to decompose the wood substrate. Based on the measurements of the size of individual fungal cultures (expressed in millimetres), it was possible to determine the relationships occurring within dual cultures. This assessment was made by determining whether the cultures were smaller or larger in size than in single cultures of the same species. In turn, the amount of dry matter loss of pine and spruce sawdust was estimated on the basis of a comparison of the final amount of sawdust (processed wood substrate) following its reduction as an effect of the fungi [Osmenda and Nawrot-Chorabik 2024].

The methods described were used to assess precisely the development of fungi that differed in terms of food preferences (saprotroph, pathogen, endophyte) and their individual growth rates. The first experiment showed the variability and intensity of the growth rates of the colonizing fungi. The main values for the sizes of individual fungal cultures colonizing pine wood are presented in Table 2. The fungal species that developed the largest cultures were *P. gigantea* – a saprotroph, *H. annosum* – a strong pathogen, *P. pini* – a weak pathogen, and *P. schweinitzii* – another weak pathogen, for which the average culture sizes ranged from 85.0 mm up to 90.0 mm. Based on the results, it can be concluded that the expansive development of the selected fungi is related to their food preferences. Studies by other authors confirm this assumption, as the areas of occurrence of the above-mentioned fungal species are forests of Europe, Asia and North America. It is also important to note that *P. gigantea, H. annosum*, *P. pini* and *P. schweinitzii* have developed the ability to infect and colonize trees of forest-forming species such as Scots pine, Norway spruce, Douglas fir (*Pseudotsuga menziesii* ((Mirb.) Franco), silver fir (*Abies alba* Mill.), and Sitka spruce (*Picea sitchensis* ((Bong.) Carrière) [Adomas et al. 2006; Dubreuil 1981; Hahle and Philip 2010; Łakomy and Dubino 2007; Mukrimin et al. 2019; Sierota 2013; Szewczyk et al. 2014; Woodward and Pearce 1988].

Among the fungal species tested, *P. ptychogaster* (60.0 mm) and *S. crispa* (30.0 mm) had the smallest sizes of cultures. The statistical analysis confirmed the significance of the differences between *P. ptychogaster* and *S. crispa* and the other tested fungal species (Table 2). This means that the growth of *P. ptychogaster* and *S. crispa* is much slower than that of the other fungi. This is confirmed by research by Ramos et al. [2008] and Stalpers [2000] on fungi cultures of the genus *Ptychogaster* on PDA medium. These fungi are characterized by a slow growth rate. This fact indicates that a culture of *P. ptychogaster* can be quickly colonized by fungi of other species. Also in the case of species such as *S. crispa* developing on PDA medium, a slow growth rate has been reported [Chang et al. 2004].

The results for single fungal cultures developing on spruce sawdust and PDA medium showed that the species which developed the largest cultures were *B. corium* and *F. pinicola*. Other fungi, including *Clonostachys* sp. and *C. ochraceum*, developed cultures of smaller size (Table 3). The statistical analysis revealed differences between the culture of *C. ochraceum* and the other tested fungal species (Table 3).

Table 2. Average growth values of single cultures of selected fungal species found on Scots pine. Statistical analysis performed with Tukey's RIR test. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus	Average size of fungus culture [mm]	Statistical analysis carried out with the Tukey test for selected fungi species					
		P. gigantea	*H. annosum*	*P. ptychogaster*	*P. pini*	*P. schweinitzii*	*S. crispa*
P. gigantea	90.00	x	1.0000	0.0002*	0.1968	1.0000	0.0002*
H. annosum	90.00	1.0000	x	0.0002*	0.1968	1.0000	0.0002*
P. ptychogaster	60.00	0.0002*	0.0002*	x	0.0002*	0.0002*	0.0002*
P. pini	85.00	0.1968	0.1968	0.0002*	x	0.1968	0.0002*
P. schweinitzii	90.00	1.0000	1.0000	0.0002*	0.1968	x	0.0002*
S. crispa	30.00	0.0002*	0.0002*	0.0002*	0.0002*	0.0002*	x

Explanation: x – culture of the same fungal species, * – statistically significant results

Table 3. Average growth values of single cultures of selected fungal species found on Norway spruce. Statistical analysis performed with Tukey's RIR test. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus	Average size of fungus culture [mm]	Statistical analysis carried out with the Tukey test for selected fungi species			
		B. corium	***C. ochraceum***	***Clonostachys sp.***	***F. pinicola***
B. corium	90.00	x	0.0403*	0.2468	1.0000
C. ochraceum	80.00	0.0403*	x	1.0000	0.0403*
Clonostachys sp.	85.00	0.2468	1.0000	x	0.2468
F. pinicola	90.00	1.0000	0.0403*	0.2468	x

Explanation: x – culture of the same fungi species, * – statistically significant results

This means that the growth of a *C. ochraceum* culture is much slower than that of other species such as *B. corium* and *F. pinicola*. The experiments show that these species can colonize and decompose food substrates in a much shorter time. This finding is confirmed by a study by Justad [2020], which showed that common species of rot fungi have the ability to develop on a food substrate very quickly. Common fungal species also have high capacity to adapt to changing environmental conditions. An example showing the high adaptability of common fungal species is their reported ability to adapt their growth and development to various types of food substrate, from laboratory medium to processed wood substrate of various tree species [Zarzyński 2019]. In contrast, in the case of *C. ochraceum*, its slow growth is related to the species' preference regarding ambient temperature. The development of *C. ochraceum* is favoured by lower temperatures, as is confirmed by the results of studies on *C. ochraceum* populations, which show that the species occurs in the colder regions of north-eastern Poland. The specific requirements of the species mean that its capacity to develop and to decompose the nutrient substrate is more limited than in the case of the other studied fungi [Karasiński et al. 2009].

After the experiments on the individual development of single fungi cultures, an investigation was made of the interactions between fungi growing in dual cultures. In these experiments, the growth of selected fungi, referred to as test cultures, was examined in the presence of completely different fungal cultures, referred to as testers (Table 4, Table 5). The fungal test cultures that developed the largest cultures and significantly reduced the growth of the testers were *P. gigantea, H. annosum* and *P. schweinitzii* (Table 4). *P. gigantea* was found to develop the largest cultures, ranging from 89.0 mm to 90.0 mm. The statistical analysis confirmed that *P. gigantea* significantly limited the growth potential of as many as five tester cultures (Table 4).

The results obtained here confirm the findings of other researchers, indicating that the rapid development of *P. gigantea* on media is the result of its competition for living space and nutrients with fungi of other species [Łakomy and Dubino 2007; Małecka et al. 2012; Poppe et al. 2003; Sierota 2013; Żółciak 2016]. An excellent example of this phenomenon is the interaction of *P. gigantea* with the dangerous pathogen *H. annosum*. The experiment showed that *P. gigantea* was the only species to inhibit the development of *H. annosum*. An advantage of *P. gigantea* in the colonization and reduction of cultures of other fungi is its ability to change the structure of hyphae and to perform cytoplasmic vacuolization of neighbouring fungi [Behrendt and Blanchette 2001]. As a result, the ability of *P. gigantea* to strongly limit the growth of other fungi has led to its application as a biopreparation to combat pathogens such as *H. annosum* in coniferous stands, and offers great potential for the development of other innovative fungicides [Adomas et al. 2006; Body 2000].

It was also observed that the *H. annosum* test culture caused severe restriction of the growth of three testers, and the *P. schweinitzii* test culture restricted the growth of two testers. These results were confirmed by the statistical analysis (Table 4). Studies described in the literature have shown that biological chemical compounds play a major role in limiting fungal growth in dual cultures. These have been studied using the example of the dangerous pathogen *H. annosum*. The defensive capability of *H. annosum* against colonization by other fungal species is due to the toxic metabolites of fommanoxin that it produces, which have antibiotic properties that make *H. annosum* cultures resistant to the harmful effects of other fungal species [Sonnenbichler et al. 1993].

Table 4. Average growth rates of dual fungal cultures isolated from Scots pine wood. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus/ culture tested	Average size of test culture [mm]	Species of fungus/tester	The average size of the tester [mm]	Statistical analysis results of Tukey's post-hoc test				
				Species of fungus/tester				
				H. annosum	*P. ptychogaster*	*P. pini*	*P. schweinitzii*	*S. crispa*
P. gigantea	89.00	*H. annosum*	70.00	x	0.0001	0.0001	0.0001	0.0001
	90.00	*P.ptychogaster*	15.00	0.0001	x	0.0240	0.0001	0.0003
	90.00	*P. pini*	20.00	0.0001	0.0240	x	0.0001	0.0875
	90.00	*P. schweinitzii*	90.00	0.0001	0.0001	0.0001	x	0.0001
	90.00	*S. crispa*	24.00	0.0001	0.0003	0.0875	0.0001	x
				Species of fungus/tester				
Species of fungus/ culture tested	Average size of test culture [mm]	Species of fungus/tester	The average size of the tester [mm]	*P. gigantea*	*P. ptychogaster*	*P. pini*	*P. schweinitzii*	*S. crispa*
H. annosum	70.00	*P. gigantea*	89.00	x	0.0001	0.9383	0.0001	0.0001
	90.00	*P. ptychogaster*	20.00	0.0001	x	0.0001	1.0000	0.0130
	90.00	*P. pini*	90.00	0.9383	0.0001	x	0.0001	0.0001
	90.00	*P. schweinitzii*	20.00	0.0001	1.0000	0.0001	x	0.0130
	52.00	*S. crispa*	15.00	0.0001	0.0130	0.0001	0.0130	x
				Species of fungus/tester				
Species of fungus/ culture tested	Average size of test culture [mm]	Species of fungus/tester	The average size of the tester [mm]	*P. gigantea*	*H. annosum*	*P. pini*	*P. schweinitzii*	*S. crispa*
P. ptychogaster	15.00	*P. gigantea*	90.00	x	1.000	0.558	1.000	0.041
	20.00	*H. annosum*	90.00	1.000	x	0.558	1.000	0.041
	45.00	*P. pini*	72.00	0.558	0.558	x	0.558	1.000
	24.00	*P. schweinitzii*	90.00	1.000	1.000	0.558	x	0.041
	27.00	*S. crispa*	34.00	0.041	0.041	1.000	0.041	x

				Species of fungus/tester			
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of fungus/tester**	**The average size of the tester [mm]**	***P. gigantea***	***H. annosum***	***P. ptychogaster***	***P. schweinitzii***	***S. crispa***
P. pini	20.00	*P. gigantea*	90.00	x	1.0000	0.0001	1.000	0.0001
	90.00	*H. annosum*	90.00	1.000	x	0.0001	1.000	0.0001
	72.00	*P. ptychogaster*	45.00	0.0001	0.0001	x	0.0001	0.353
	31.00	*P. schweinitzii*	90.00	1.000	1.000	0.0001	x	0.0001
	42.00	*S. crispa*	42.00	0.0001	0.0001	0.353	0.0001	x

				Species of fungus/tester			
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of ungus/tester**	**The average size of the tester [mm]**	***P. gigantea***	***H. annosum***	***P. ptychogaster***	***P. pini***	***S. crispa***
P. schweinitzii	90.00	*P. gigantea*	90.00	x	1.000	0.0001	1.000	0.0001
	20.00	*H. annosum*	90.00	1.000	x	1.000	1.000	1.000
	90.00	*P. ptychogaster*	42.00	0.0001	0.0001	x	0.0001	0.0001
	31.00	*P. pini*	90.00	1.000	1.000	0.0001	x	1.000
	90.00	*S. crispa*	12.00	0.0001	0.0001	0.0001	0.0001	x

				Species of fungus/tester			
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of fungus/tester**	**The average size of the tester [mm]**	***P. gigantea***	***H. annosum***	***P. ptychogaster***	***P. pini***	***P. schweinitzii***
S. crispa	24.00	*P. gigantea*	90.00	x	1.000	0.041	1.000	1.000
	15.00	*H. annosum*	52.00	1.000	x	0.041	1.000	1.000
	34.00	*P. ptychogaster*	27.00	0.041	0.041	x	0.041	1.000
	42.00	*P. pini*	42.00	1.000	1.000	0.041	x	1.000
	12.00	*P. schweinitzii*	90.00	1.000	1.000	1.000	1.000	x

Explanation: x – culture of the fungal species that is the tester

In the case of *P. pini*, the test culture caused a reduction in the growth of only one tester. The tests with *P. ptychogaster* and *S. crispa* test cultures showed that they were dominated by the majority of testers. The growth of *P. ptychogaster* was limited by four tester species, and that of *S. crispa* by five testers. However, despite the fact that *S. crispa* developed a small culture size, it was observed that testers of other fungi had much smaller size. In addition to slow growth, *S. crispa* mycelium has the ability to secrete strong antibiotic substances named ScI and ScII, which are toxic to cultures of other fungi [Woodward et al. 1993]. This fact may be used in the development of innovative methods and biologically active substances that would enable the protection of raw wood material in forest landings. This assumption is confirmed by research by Kim et al. [2013], which shows that the compounds ScI and ScII secreted and isolated from the fruiting body of *S. crispa* have a strong fungicidal effect, which can be used to create effective fungicides.

Regarding the interactions occurring within the dual fungal cultures isolated from spruce wood, it was found that the species whose test culture reached the largest dimensions was *B. corium*, which had a test culture 75.0 mm to 90.0 mm in size. This species also caused a very pronounced reduction in growth and size compared with the two testers and inhibited the further growth potential of *F. pinicola* (Table 5). Studies confirm that one of the survival strategies of fungi is based on competition between them, which in the present case consisted in rapid reduction of the growth of another fungal species by limiting its living space [Piętka 2016]. The results of the statistical analysis confirm that the differences between the average sizes of cultures of individual fungi species are significant (Table 5). In the case of *Clonostachys* sp. and *F. pinicola* test cultures, it was observed that these fungi inhibited the further growth of two testers and markedly limited the growth of one tester (Table 5). The ability of *Clonostachys* sp. to limit the growth of other fungi is due to the secretion by its mycelium of volatile organic compounds that are toxic to other organisms. This phenomenon is confirmed by Zang et al. [2008], who showed that a *Clonostachys* sp. culture fights *Botrytis cinerea* (Pers.) spores, a dangerous pathogen of fruit and vegetables that causes their rotting [Williamson et al. 2007]. In the experiment, it was also observed that the size of the *C. ochraceum* test culture was reduced by three tester species. The statistical analysis confirms that no significant differences were observed for *C. ochraceum* (Table 5).

The next stage of the experiments investigating the size of single and dual fungal cultures was to examine the intensity of decomposition of various types of sawdust. The main results for the reduction of the mass of sapwood and heartwood sawdust from Scots pine and Norway spruce by selected fungal species under the conditions of the described experiments are presented in Tables 6 and 7.

Based on the results on the ability of single fungal cultures to decompose pine wood, it was found that the sawdust was most extensively decomposed by *P. schweinitzii, P. gigantea*, *P. pini* and *P. ptychogaster*. *Phaeolus schweinitzii* mycelium caused a reduction in the mass of sapwood sawdust by 19.0%, while in the case of *P. gigantea* the reduction was 12.6%, for *P. pini* it was 11.8%, and for *P. ptychogaster* it was 11.1% (Table 6, Fig. 3). Different results from those reported in the literature were obtained in the case of *P. pini*. The experiment showed that *P. pini* led to significantly greater decomposition of sapwood than heartwood sawdust; in the case of heartwood sawdust the reduction was only 2.0% (Table 6, Fig. 3). According to other authors, *P. pini* decomposes mainly heartwood in pine [Szewczyk 2015]. The surprising effect obtained in this study may be due to the fact that the growth and colonization of food substrates by *P. pini* is slower than in the case of tested species characterized by expansive growth, such as *P. gigantea*. Another reason for the low level of decomposition of the heartwood substrate is probably the fact that the fungus culture was grown on processed food substrate and not on solid heartwood, a large share of which is found in pines of older age classes [Tomusiak and Zarzyński 2019]. The phenomenon of decomposition of particular types of wood, i.e. sapwood and heartwood, is particularly important in the case of raw wood (logs) or chips and sawdust stored for a long time on landings, where sapwood and sawdust and chips made from it are exposed to increased decomposition by the above-mentioned species of fungi. Therefore, it was important to carry out tests on wood processed in the form of sawdust. However, in the case of decomposition of heartwood sawdust by other species, it was found that the most intensive decomposition of the wood substrate was caused by the action of *P. schweinitzii* and *S. crispa*.

Phaeolus schweinitzii reduced the amount of heartwood sawdust by 15.0%, while *S. crispa* reduced it by 13.4% (Table 6). In the case of *S. crispa*, the possibility of intensive decomposition of the wood substrate is confirmed by a study conducted by Lee et al. [2004], which examined the development of *S. crispa* on a substrate in the form of larch sawdust. *S. crispa* cultures exhibited intensive growth and decomposition of larch sawdust prepared from heartwood. Based on the statistical analyses, it was found that there are significant differences between the decomposition of sapwood and heartwood sawdust in the case of *P. gigantea, P. pini* and *S. crispa* (Table 6). The results show that each of these species decomposed the sapwood substrate more intensely. *P. gigantea* produced an 8.0% greater reduction in sapwood than in heartwood sawdust. In the case of *Porodaedalea pini* the difference was 9.8%, and in the case of *S. crispa* it was 2.0%.

Table 5. Average growth rates of dual fungal cultures isolated from Norway spruce wood. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus/ culture tested	Average size of test culture [mm]	Species of fungus/tester	The average size of the tester [mm]	Statistical analysis results of Tukey's post-hoc test		
				Species of fungus/tester		
				C. ochraceum	***Clonostachys* sp.**	***F. pinicola***
B. corium	90.00	*C. ochraceum*	20.00	x	0.0002	0.0002
	75.00	*Clonostachys* sp.	45.00	0.0002	x	0.0002
	90.00	*F. pinicola*	90.00	0.0002	0.0002	x
				Species of fungus/tester		
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of fungus/tester**	**The average size of the tester [mm]**	***B. corium***	***Clonostachys* sp.**	***F. pinicola***
C. ochraceum	20.00	*B. corium*	90.00	x	0.0623	1.0000
	30.00	*Clonostachys* sp.	85.00	0.0623	x	0.0623
	20.00	*F. pinicola*	90.00	1.0000	0.0623	x
				Species of fungus/tester		
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of fungus/tester**	**The average size of the tester [mm]**	***B. corium***	***C. ochraceum***	***F. pinicola***
Clonostachys sp.	45.00	*B. corium*	75.00	x	0.0001	0.0001
	85.00	*C. ochraceum*	30.00	0.0001	x	0.0049
	43.00	*F. pinicola*	40.00	0.0001	0.0049	x
				Species of fungus/tester		
Species of fungus/ culture tested	**Average size of test culture [mm]**	**Species of fungus/tester**	**The average size of the tester [mm]**	***B. corium***	***C. ochraceum***	***F. pinicola***
F. pinicola	90.00	*B. corium*	90.00	x	0.0001	0.0001
	90.00	*C. ochraceum*	20.00	0.0001	x	0.0001
	40.00	*Clonostachys* sp.	43.00	0.0001	0.0001	x

Explanation: x – culture of the fungus species that is the tester

Table 6. Reduction in amounts of sapwood and heartwood sawdust from Scots pine after decomposition by selected fungal species. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus	Reduced weight of sapwood sawdust [g]	Reduced weight of heartwood sawdust [g]	t	df	p
P. gigantea	0.3495	0.3815	-6.9013	6	0.0005*
H. annosum	0.3675	0.3708	-0.5535	6	0.5999
P. ptychogaster	0.3555	0.3820	-1.3539	6	0.2245
P. pini	0.3528	0.3920	-11.5429	6	0.0000*
P. schweinitzii	0.3240	0.3400	-1.1790	6	0.2830
S. crispa	0.3540	0.3463	2.9162	6	0.0268*

Explanation: * – statistically significant results

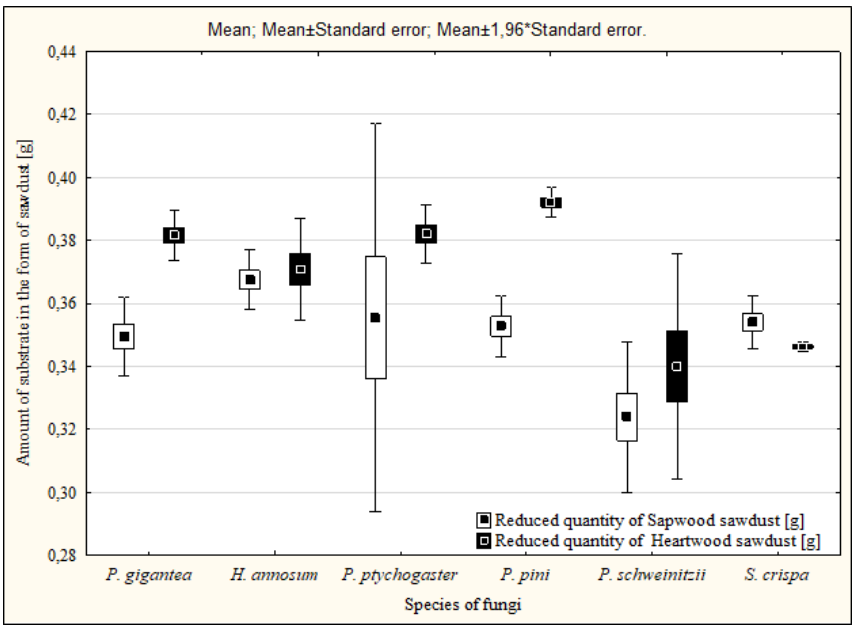

Fig. 3. Diagram showing 95% confidence intervals for reductions in amounts of sapwood and heartwood sawdust from Scots pine by selected fungal species

In the experiment investigating how single cultures of fungal species decomposed spruce sapwood and heartwood, it was found that the greatest reduction of sapwood and heartwood sawdust substrate was produced by *F. pinicola* and *B. corium* cultures (Table 7). *F. pinicola* reduced the mass of the sapwood sawdust by 28.5% and the heartwood sawdust by 26.5%, while *B. corium* caused reductions of 11.0% in the case of sapwood and 13.9% in the case of heartwood sawdust (Table 7, Fig. 4). The experiment showed the potential decomposition of wood substrate by *Clonostachys* sp., which is not a rot fungus. The ability of *Clonostachys* sp. to decompose wood substrate is confirmed by studies conducted on *Clonostachys rosea* ((Fr.) Schroers, Samuels, Seifert et W. Gams) and *Clonostachys rosea* f. *catenulata* ((J.C. Gilman et E.V. Abbott) Schroers). These fungi have the ability to decompose organic matter in the form of decaying plants and birch wood [Rybczyńska-Tkaczyk and Korniłłowicz-Kowalska 2018]. It is very likely that the ability of *Clonostachys* sp. to decompose food substrates is related to the structure of the substrate, which was fragmented, making it easier for the species' mycelium to penetrate into the wood cells and take up nutrients. The statistical analyses showed that statistically significant values occur only in the case of *F. pinicola*, which shows that this fungi colonizes the processed food substrate in the form of white sawdust at a faster rate (Table 7).

Table 7. Reduction in amounts of sapwood and heartwood sawdust from Norway spruce after decomposition by selected fungal species. Statistically significant results ($p < 0.05$) are marked * in the table

Species of fungus	Reduced weight of sapwood sawdust [g]	Reduced weight of heartwood sawdust [g]	t	df	p
B. corium	0.3558	0.3443	0.4771	6	0.6502
C. ochraceum	0.3743	0.3728	0.7703	6	0.4703
Clonostachys sp.	0.3788	0.3773	0.3716	6	0.7229
F. pinicola	0.2860	0.2940	-5.2372	6	0.0019*

Explanation: * – statistically significant results

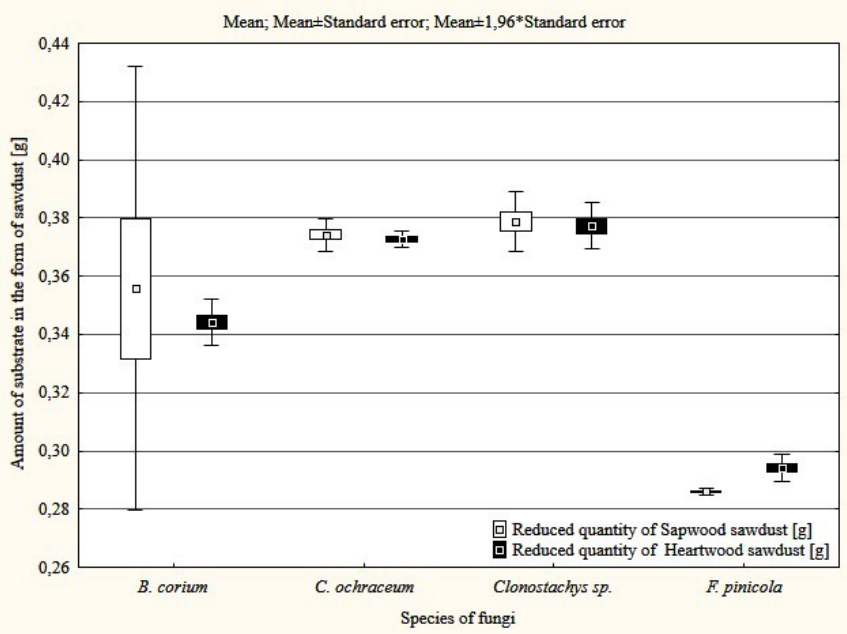

Fig. 4. Diagram showing 95% confidence intervals for reductions in amounts of sapwood and heartwood sawdust from Norway spruce by selected fungal species

The last stage of the research, which concerned the overall impact of fungi on wood substrate decomposition, involved determining the average loss of sapwood and heartwood sawdust. These results provide a summary of the impact of fungi which, through their growth and development, cause damage to sawdust and chips, reducing their quality.

Analysis of variance performed using the Kruskal–Wallis test ($H(5, N=42) = 15.485$, $p = 0.0085$) indicated significant differences between some means (Table 8). Differences were observed in the case of *P. schweinitzii*, where the average loss of sapwood and heartwood sawdust at the end of the experiment was 17.0% (Table 8). Compared with other fungi, *P. schweinitzii* caused greater reduction of both types of sawdust: greater than *P. gigantea* by 8.4%, *H. annosum* by 9.3%, *P. ptychogaster* by 5.9%, *P. pini* by 8.6%, and *S. crispa* by 4.5% (Table 8). The results of the experiment showed that *P. schweinitzii* is the fungus with the ability to decompose the largest amount of pine sawdust. This species causes large losses in tree stands due to its expansive colonization of wood in the middle part of the trunk and root collar, which ultimately leads to significant losses in the quality of the harvested raw material [Hagle and Filip 2010]. Due to the large loss in quality and weight of the wood raw material caused by *P. schweinitzii*, this species of fungus poses a significant threat to the production of good-quality chips and wood used in the furniture industry.

Table 8. Averaged values of reduction in mass of sapwood and heartwood sawdust from Scots pine. Statistically significant results ($p < 0.05$) are marked * in the table

Non-parametric Kruskal-Wallis analysis of variance		
H	N	p
5	42	0.0085

Tukey's Statistical Analysis

Species of fungus	**Average value of reduced amount of sapwood and heartwood sawdust [g]**	***P. gigantea***	***H. annosum***	***P. ptychogaster***	***P. pini***	***P. schweinitzii***	***S. crispa***
P. gigantea	0.3655	x	1.0000	1.0000	1.0000	0.1364	1.0000
H. annosum	0.3691	1.0000	x	1.0000	1.0000	0.0071*	0.2945
P. ptychogaster	0.3555	1.0000	1.0000	x	1.0000	1.0000	1.0000
P. pini	0.3665	1.0000	1.0000	1.0000	x	0.1630	1.0000
P. schweinitzii	0.3320	0.1364	0.0071*	1.0000	0.1630	x	1.0000
S. crispa	0.3501	1.0000	0.2945	1.0000	1.0000	1.0000	x

Explanation: x – culture of the same fungal species, * – statistically significant results

Table 9. Averaged values of reduction in mass of sapwood and heartwood sawdust from Norway spruce. Statistically significant results ($p < 0.05$) are marked * in the table

Non-parametric Kruskal-Wallis analysis of variance		
H	N	p
3	32	0.0002

Tukey's Statistical Analysis

Species of fungi	**Average value of reduced amount of sapwood and heartwood sawdust [g]**	***B. corium***	***C. ochraceum***	***Clonostachys* sp.**	***F. pinicola***
B. corium	0.3500	x	1.0000	0.4716	0.0853
C. ochraceum	0.3735	1.0000	x	1.0000	0.0047*
Clonostachys sp.	0.3780	0.4716	1.0000	x	0.0002*
F. pinicola	0.2900	0.0853	0.0047*	0.0002*	x

Explanation: x – culture of the same fungal species, * – statistically significant results

In the case of results on the average reduction of sapwood and heartwood spruce sawdust, analysis of variance performed using the Kruskal–Wallis test ($H(3, N=32) = 19.848$, $p = 0.0002$) again showed potentially significant differences between some of the means (Table 9). Interpreting the post hoc Tukey test, it was found that there are significant differences in the averaged values of weight loss in the case of *F. pinicola*, which reduced the mass of sawdust by 27.5% (Table 9). Among the studied fungi, *F. pinicola* caused the greatest reduction of both types of spruce sawdust. *F. pinicola* caused a greater average reduction than *B. corium* by 15.0%, *C. ochraceum* by 20.9%, and *Clonostachys* sp. by 22.0%. The expansiveness of this species is also confirmed by studies by Justad [2020], in which it was found that *F. pinicola* was able to decompose a large amount of wood substrate in the form of sawdust made from grey alder wood (*Alnus incana* (L.) Moench) in a short period of time.

Conclusions

1. Interspecies interactions observed in in vitro cultures of fungi and their impact on pine and spruce sawdust

Certain fungal species have the ability to grow intensively on pine and spruce sawdust and strongly inhibit the growth other fungal species in dual cultures; these are *P. gigantea, H. annosum, P. pini, P. schweinitzii*, *B. corium* and *F. pinicola*.

The non-rot fungus *Clonostachys* sp. caused a slowing of the growth and development of other fungi tested with it in dual cultures. This effect is likely a consequence of chemicals secreted by the species that limit the growth of other fungal species.

The fungi *Phaeolus schweinitzii, P. gigantea, B. corium* and *F. pinicola* caused very intensive decomposition of sapwood sawdust. Also, *P. schweinitzii* and *F. pinicola* caused the greatest loss of heartwood sawdust.

Decomposition of the wood substrate is a serious problem for the heating industry, which uses processed wood biomass in the form of chips and sawdust for the production of pellet and briquettes. The results regarding the average reduction of sawdust showed that the greatest decomposition of the substrate was caused by such species as *P. schweinitzii, P. ptychogaster, S. crispa* and *F. pinicola*.

2. Potential use of research to protect the quality of obtained wood raw material against the direct impact of fungi

Species of fungi common in the forest environment and capable of faster wood substrate colonization are the greatest challenge in the protection of quality raw wood material against decomposition caused by fungi. It should also be noted that rot fungi occurring on solid pine and spruce wood lead to rapid decomposition of the treated raw wood material, including sawdust.

Dual cultures provide a basis for experiments aimed at developing and producing innovative methods and fungicides for protecting wood on forest landings before it is collected by the buyer.

The interactions that occurred between different fungi have important implications for the wood industry, because the studied interspecies interactions can be used to effectively protect valuable raw wood material stored in conditions that are ideal for the development of fungal pathogens. Modernized protection of wood raw materials is based on the development of an innovative methodology related to the conditions and duration of storage of wood raw materials, among others by protecting valuable wood assortments in warehouses using innovative fungicides developed on the basis of the interactions identified between individual fungal cultures.

There is a possibility that *B. corium* can be used to protect wood stored in forest landings in order to directly protect the raw wood material against infection and to minimize progressive wood decomposition with visible symptoms of rot, such as wood colour change. As a result, the stored raw wood material will not deteriorate in quality and will not need to be reclassified to lower quality classes.

3. Summary of conclusions

The final results obtained in this work, in conjunction with studies by other authors, show that the fungi investigated here are currently the greatest threat to the extraction of good quality raw wood material for use in the form of sawdust or chips, of which the technical properties are impaired as a result of fungal decomposition. For this reason, the research constitutes a solid basis for improvements in the securing and protection of sawdust and wood chips that are important for the wood and energy industries.

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