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ORIGINAL ARTICLE

Characterization of wood dust emission according to some wood species in 3D machining applied with CNC machine

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Abstract
The use of CNC machines for woodworking is becoming increasingly widespread due to advancing technology. In this study, while 3D processing is performed on wood materials using a CNC machine, the aim is to determine wood dust emissions (PM2.5, PM10) according to processing parameters and wood species. Yellow pine, spruce, chestnut, sapelli, and beech are wood species frequently preferred in furniture businesses. Utilizing a CNC machine equipped with 2 mm and 10 mm diameter cutting tools, the wooden material was machined at a spindle speed of 18,000 RPM, a plunge rate of 4000 mm/min, and a cutting speed of 8000 mm/min. For the study, a 3D-modeled motif with curved lines was selected and applied to wooden prisms measuring 30 cm × 30 cm × 30 mm (width, length, thickness).
In conclusion, Yellow pine, with its high hardness and dense structure, generates significantly more dust than spruce during CNC machining. This result reveals that different wood species exhibit different levels of environmental impact during CNC processing. This underscores the urgent need for appropriate air filtration and emission control systems, particularly for woods that produce high emissions. Fine cutting edges effectively reduce PM2.5 and PM10 concentrations, enhancing workplace air quality. By reducing exposure to wood dust, which is harmful to human health, this study plays a crucial role in addressing this pressing issue and allows for the implementation of suitable arrangements with minimal chip removal for CNC parameters.

1 Introduction

In many woodworking and furniture production businesses, appropriate machines are used. In recent years, with the advancement of technology, CNC machines have become increasingly widespread in this field. However, the wood dust produced during the operation of CNC machines disperses into the workplace environment, posing significant health risks to workers. If the spread of wood dust within facilities using CNC machines is not adequately controlled, it can severely impact employees' health (Nasir & Cool 2020; Matrat et al. 2019).

The mechanical processes involved in wood processing lead to the formation of dust, known as particulate matter (PM), during the conversion of wood into furniture, boards, and other factory-made products (Fujimoto et al. 2011). PM generated by CNC machines operating at high production speeds tends to be smaller in diameter and exists at higher concentrations. If dust extraction systems and integrated mechanisms fail to sufficiently remove airborne wood dust, fine particles can accumulate in the working area of CNC machines, posing a significant health risk (Krimpenis, 2016).

Wood dust ranges in particle size from 1 to 500 µm and is classified into coarse, medium, or fine dust categories. These particles can spread in large quantities and significantly accumulate in the environment (Hlásková et al. 2016; Markova et al., 2018; Igaz et al., 2019; Kminiak & Dzurenda 2019). The amount of PM produced varies depending on the properties of the wood species, the CNC machine's processing parameters, the duration of processing, and the CNC technology applied (Palmqvist & Gustafsson 1999; Ratnasingam et al. 2010; Fujimoto

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et al. 2011; Hlásková et al. 2015; Očkajová et al. 2016; Očkajová et al. 2018).

The anatomical structures of tree species, their growing environments, and regional characteristics can significantly impact human health. Fine particles in the working environment pose serious health risks, leading to issues such as respiratory disorders among wood industry workers (Bozkurt & Bozkurt 1979; Kucerka et al. 2023; Tureková et al. 2019; Hlásková et al. 2015). The health effects of wood dust also depend on the wood species. For instance, dust from beech and oak trees can cause cancer, while dust from poplar, birch, and willow trees may lead to skin diseases (Puntaric et al., 2005; Proto et al. 2010; Lee et al. 2011; Mrackova et al., 2016). Additionally, medium-density fiberboards (MDF) release not only fine particles but also harmful chemicals like formaldehyde, causing workplace air pollution (Rogoziński, 2018).

By-products such as shavings and fine dust generated during wood processing can accumulate in the work environment and potentially cause significant problems if sufficient control measures are not applied. These risks can be mitigated by implementing effective dust control measures and efficient dust extraction systems. However, CNC machines present a significant challenge as they produce fine dust particles, and existing dust extraction systems are often inadequate in capturing these small particles (Kminiak et al. 2021; Rogoziński et al., 2015; Rogoziński et al., 2017). Controlling PM emissions from CNC and other woodworking machines requires optimizing processing parameters and ensuring the efficient operation of dust extraction systems. Clean air circulation plays a vital role in this process (Jug et al. 2016). Dust generated by cutters producing large chips during CNC operations spreads through spiral air currents, reducing the efficiency of dust extraction systems. This can cause dust to collide with suction device pipes and return to the processing area. Additionally, cleaning operations using compressed air result in secondary dust dispersion (Banski & Kminiak 2018; Kminiak & Banski 2018).

Numerous studies have investigated methods to reduce the effects of wood dust generated during CNC wood processing operations. Pangestu et al. (2022) determined that adjusting cutting blades to a 75° angle significantly reduces wood dust formation. Larger inclination angles result in smaller chip particles with lower kinetic energy (Darmawan et al. 2011; Novayer et al., 2021). In milling operations with helical cutting edges, slope angles between 5°–10° have been found effective in minimizing PM emissions (Heisel et al. 1993). Kucerka et al. (2023) compared the particle sizes of solid wood and MDF dust, finding that MDF dust particles are smaller in diameter. Additionally, various studies have examined the granulometric properties of CNC-generated dust, observing that it typically consists of small particles (Čavlović & Bešlić, 2021; Banski & Kminiak 2018; Dzurenda 2019).

This study aims to analyze the size distribution of wood dust particles generated during the machining of five different wood species using a CNC machine with 3D motifs. The machine operates at constant spindle, cutting, and plunge speeds, utilizing two different cutter types. The primary objective is to investigate differences in the concentration of respirable wood dust generated during CNC processing with respect to wood species and cutter diameters. In this context, this study will propose recommendations to reduce source-level dust exposure caused by CNC machines commonly used in the industry.

2 Materials and methods

2.1 CNC machine

This study used a 4-axis CNC machine with a working area of 2100 × 2800x250 mm and a power of 9 kW (24,000 rpm) from the Italian brand Megatron 2128 (Bursa/Turkey). The DVP vacuum motor has a capacity of 305 m^3 per hour and features an 8-eyed vacuum table, and each of these eyes can be controlled individually. Additionally, there is an 8-slot magazine for tool change operations. The CNC machine used in this study is shown in Fig. 1. The "Alphacam 2023.1/ Hexagon" program is used by the CNC machine, where all drawings and modeling are performed, and then G codes are generated.

Fig. 1 Megatron CNC machine

2.2 Cutting tools for CNC machines

The CNC machine has 8 tool holders. This study used a Netmak brand cutting tool with a diameter of 10 mm (Thick tool) Ø10 × 30x82 d.14 Dimensions 2 pieces (the model name is 0450 hard metal plate end milling cutter) and a 0° traditional edge angle for rough machining. A Mikron carbide cutter with a diameter of 2 mm (Thin tool) Ø2 × 35x80xØ6, a 20° helix angle 2 pieces (the model name is micron ball nose carbide milling cutter), and double cutting edges are preferred for fine operations. The lifespan of CNC machine tools typically ranges from several hundred to several thousand hours, depending on operational conditions and maintenance practices (BuyCNC. (n.d.).). However, the exact lifespan must be evaluated based on parameters like the type of tool, operating conditions, and maintenance frequency. Based on this evaluation, the lifespan of the blades used in this study was determined to be adequate for the study's objectives. Blade-related emission change rates have been considered negligible due to the sufficient lifespan of the blades and their minimal impact on dust generation during the study. Figure 2 illustrates the technical specifications and drawings of the cutters.

2.3 Wood species

Within the scope of the study, 5 different wood species were examined. In this study, Yellow pine (*Pinus sylvestris* L.), spruce (*Picea orientalis* L.), chestnut (*Castanea sativa* Mill.), sapelli (Entandrophragma cylindricum Sprague) and beech (*Fagus* orientalis Lipsky) were used as wood species. Yellow pine, spruce, chestnut and beech were supplied originally from Artvin/Türkiye origin. The origin of the exotic wood species Sapelli, which is of African origin, is West-Central-East Africa. It was supplied by a timber producer in Turkey. Wood materials are obtained from kiln-dried wood from lumber production facilities. Kiln-dried timber was preferred to achieve moisture content below 20%. Cross-sectional images of the wood species used in this study are shown in Fig. 3.

2.4 Wooden examples with 3D motifs for study

In this study, a motif with curved lines was modeled using the Alphacam software, and undulating engravings were performed. These processes resulted in a specific dispersion characterization of the wood dust. Figure 4 shows a visualization of the motif modeled.

All samples were measured individually on a CNC machine. Each species of wood was processed on a CNC machine using a thick tool with a diameter of 10 mm and a thin tool with a diameter of 2 mm. Measurements were recorded at specific intervals. For each wood species, 10 samples were produced with two copies of the same 3D motif, and the processing time for each wood species was recorded as 8 h and 13 min. Processing was carried out on the CNC machine using cutting blades with diameters of 2 and 10 mm at 18,000 revolutions per minute, with a plunge rate of 4000 mm/min and cutting speed of 8000 mm/min. The 3D motifs used in this study were applied to wooden prisms measuring 30 cm × 30 cm × 30 mm (width, length, thickness). In Fig. 5, 3D operations are shown according to the wood species.

2.5 PMs originating from wood

Wood dust was produced at specified time intervals as a result of processes carried out with 2- and 10-mm-diameter

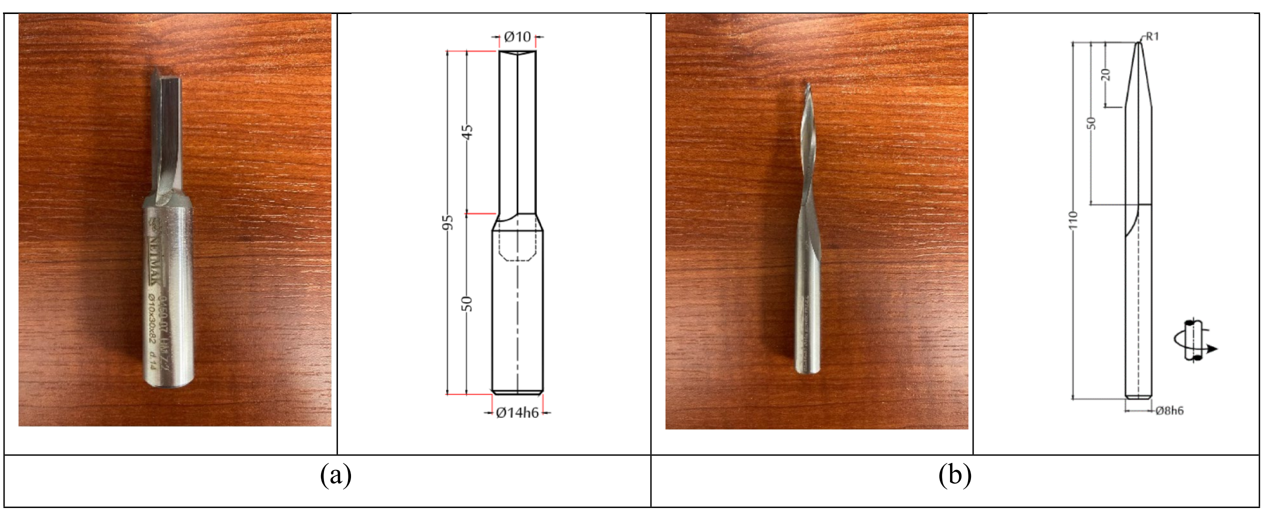

Fig. 2 CNC cutting tools with a diameter of 10 mm (a) and 2 mm (b)

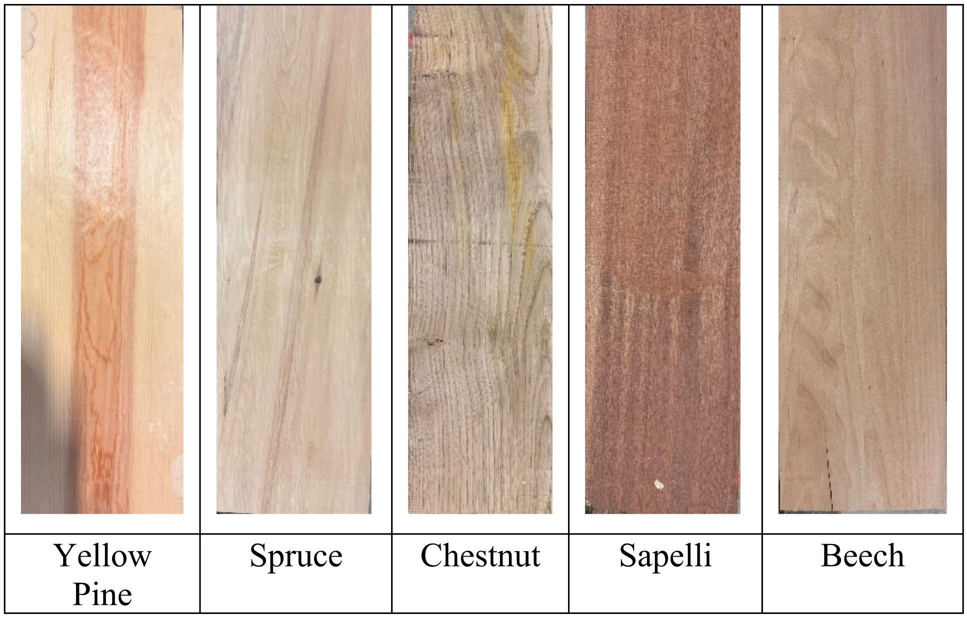

Fig. 3 Cross-sectional images of wood species

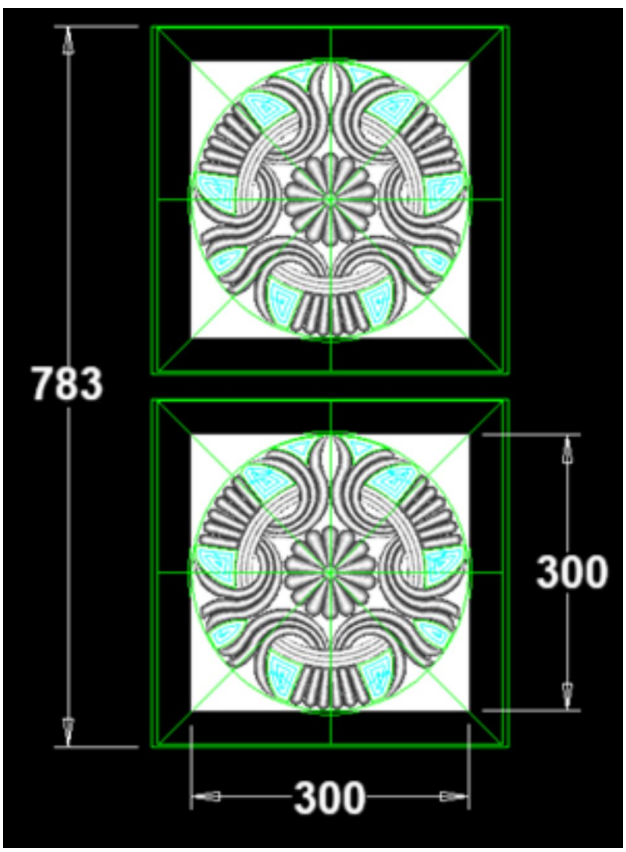

Fig. 4 Model created in Alphacam (dimensions in mm)

blades. The obtained wood powders were stored under appropriate conditions. The geometrical structure of the dust particles during formation is not considered in this study, as it can vary depending on the angle of the CNC cutter blade and fluctuations in dust concentration. The characteristics of the wood dust generated in the measurement area are shown in Fig. 6.

2.6 Measurement of PMs

This study examined the dispersion of wood dust generated during the 3D motif processing of five different species of wood on a CNC machine in a furniture workshop using the same spindle speed, cutting speed, feed rate, and cutters. A measurement device with semiconductor detection technology was used to determine the concentrations of PM2.5 and PM10. According to the data provided by the manufacturer, the measurement ranges of the detector used are 0–999 µg/ m^3 for PM2.5 and PM10.

Before starting the measurements, witness measurements were taken on Monday when the workshop had yet to commence operations. The purpose of taking witness measurements on Monday morning is to ensure that particulate matter in the air settles over the weekend, as the workshop is closed on Saturdays and Sundays. Using this method, the PM levels in the ambient air were measured at the lowest level before the workshop began and were accepted as reference levels.

Experimental measurements were conducted within the framework of different scenarios, and PM2.5 and PM10 concentrations were measured under the following conditions:

- Use thick and thin tools with an air suction system under open and closed conditions for PM2.5 and PM10 Measurements of concentrations (Scenario 1),
- Measurement of PM10 concentration using thick tools and an air suction system closed (Scenario 2),

Fig. 5. 3D processing by wood species

- Measurement of PM10 concentration using thick tools and an open air suction system open (Scenario 3).
- Measurement of PM10 concentration using thin tools and closed air suction system closed (Scenario 4),
- Measurement of PM10 concentration with the use of thin tools and an open air suction system open (Scenario 5),
- Measurement of PM2.5 concentration using thick tools and an air suction system closed (Scenario 6).
- Measurement of PM2.5 concentration using thick tools and an open air suction system open (Scenario 7),
- PM2.5 measurement using thin tools and an air suction system under closed conditions (Scenario 8),
- PM2.5 measurement using thin tools and an air suction system under open conditions (Scenario 9).

The measurement area was positioned closest to the CNC machine blades, a location chosen for its adaptability to different experimental conditions. This adaptability ensures that PMs are measured correctly at their source and that the concentrations formed during the process are detected as accurately as possible. The number of measurements taken under each experimental condition was varied according to the processing time of the CNC machine. The measurements were conducted at fixed 30-s intervals and varied in each scenario according to the species of cutting tool and the effect of the air suction system. This adaptable arrangement effectively simulates the variable processing times under different production conditions.

2.7 Comparison of PM emissions in different wood species and CNC-processed scenarios

This study applied statistical analyses to evaluate the differences between scenarios using experimental data. Differences between the wood species and scenarios were analyzed using the Kruskal–Wallis test, and the Dunn test was used to identify significant differences. All statistical analyses were performed using MATLAB R2024a software.

Fig. 6 Wood dust formed by rough and fine-grained processing

The Kruskal–Wallis test is a nonparametric statistical test used to evaluate median differences between independent groups. It is preferred when the data do not show a normal distribution and is an effective method for comparing multiple groups. The Kruskal–Wallis test, which is a practical extension of the Wilcoxon-Mann–Whitney test, can be applied to multiple independent samples. It tests whether the medians of the groups are equal, providing a powerful tool for real-world data analysis. The p-value obtained from the test is generally evaluated at the 0.05 significance level; if it is below this level, then a statistically significant difference between the groups (Ostertagová et al. 2014).

The Dunn test is a post hoc analysis applied after the Kruskal–Wallis test and is used to determine the median differences between groups. If the Kruskal–Wallis test finds a significant difference between groups, the Dunn test identifies which groups have this difference and makes pairwise comparisons (Al-Shammari, 2021; Kamrath 2023).

3 Results and discussıon

In this study, measurements of PM2.5 and PM10 emissions generated during operations performed with a CNC machine under different scenarios were taken. Experimental measurements were conducted using five different wood species: Yellow pine, sapelli, chestnut, spruce, and beech. Concentrations were recorded under the following conditions: cutter tip type (thick and thin) and air suction system (open and closed). Statistical analyses were conducted using the Kruskal–Wallis test to detect intergroup differences, and significant differences were identified using the Dunn test.

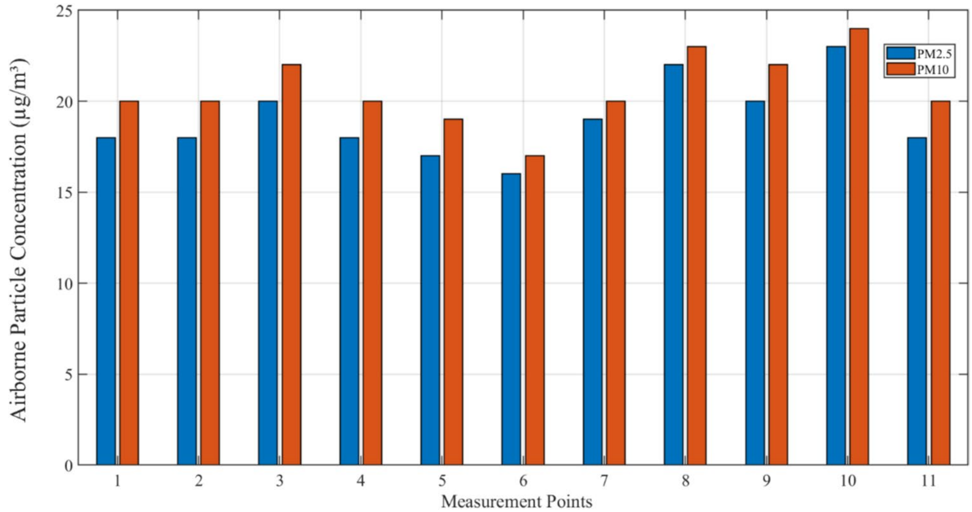

Fig. 7 Initial reference measurements in the workshop environment

3.1 PM2.5 and PM10 measurements

The detailed measurement results for each wood species and scenario, as well as PM2.5 and PM10 emissions under different conditions, were examined.

3.1.1 Initial reference measurements: PM2.5 and PM10 levels in the workshop environment

Figure 7 shows the reference measurements taken before starting the workshop. The measurements were carried out using the lowest PM levels in the ambient air as a reference. This method assumes that the particles remaining in the air have settled because the workshop was closed over the weekend.

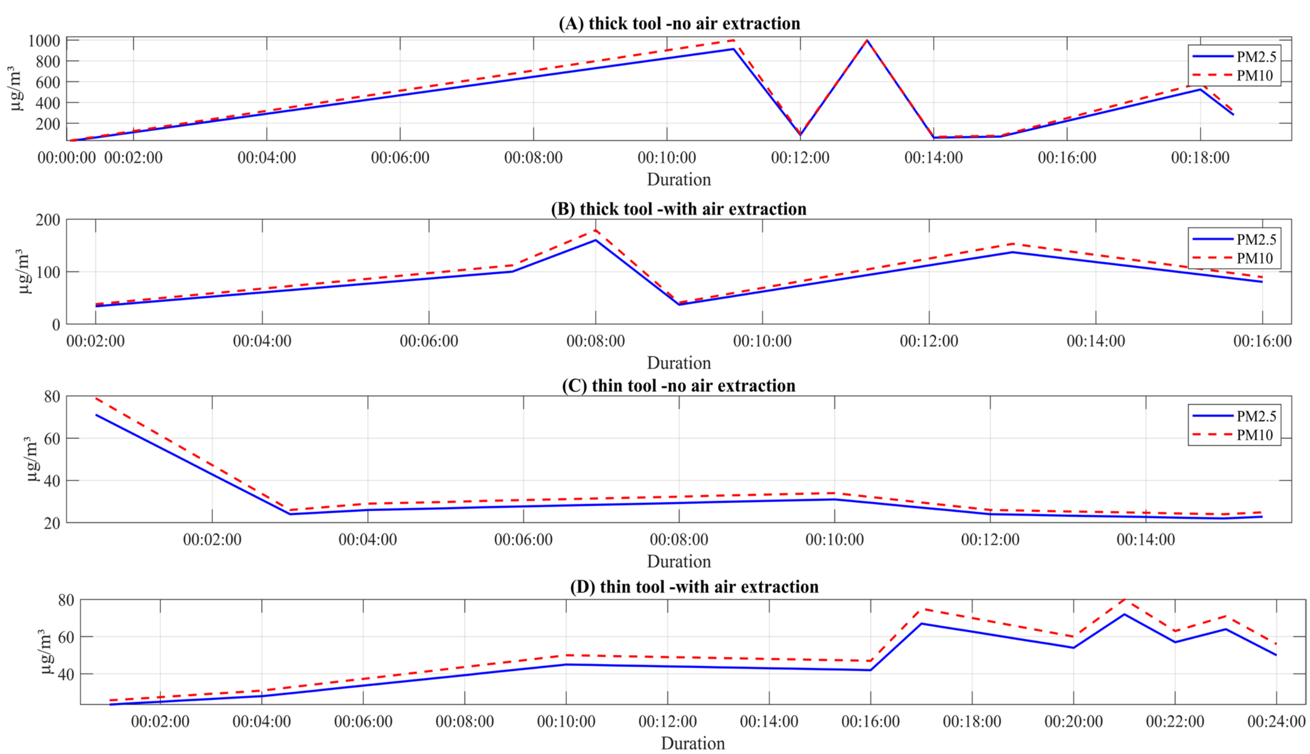

Fig. 8 PM2.5 and PM10 concentration measurement results for different scenarios during the processing of Yellow pine

The reference measurements conducted before the workshop indicated that the PM2.5 and PM10 concentrations in ambient air were generally low. At the measurement points, PM2.5 values ranged between 16 μg/m^3 and 23 μg/m^3, while PM10 values showed a similar trend, ranging between 17 μg/m^3 and 24 μg/m^3. These comprehensive data indicate a generally clean indoor air quality in the workshop environment before the activities.

3.1.2 Emission measurements during the production of Yellow pine

Figure 8 presents the PM2.5 and PM10 measurement results from operations conducted with Yellow pine under different scenario conditions.

Experimental measurements revealed temporal changes in PM2.5 and PM10 concentrations under different scenarios in CNC machines. The data were obtained using "open and closed air intake systems" and "thick and thin tools."

During the first 17 min in Fig. 8, when the air suction system was off and the tools were used, the levels of PM2.5 and PM10 gradually increased. Under these conditions, the PM10 value, initially 28 μg/m^3, reached a maximum level of 999 μg/m^3 by the 10th minute. Similarly, PM2.5 concentration increased significantly during the same period, reaching 914 μg/m^3. These results indicate that emissions rapidly increase without air suction and that environmental PM concentrations increase significantly. In Fig. 8-B, a significant decrease in PM concentrations was observed during operations when the air intake system was open and the thick tool was used. The PM2.5 and PM10 concentrations decreased to 34 μg/m^3 and 38 μg/m^3, respectively. It was observed that the air suction system with the thin tool maintained lower PM2.5 and PM10 concentrations under closed conditions. For example, while the PM10 concentration was measured at 31.5 μg/m^3 in the first measurement, it continued to increase gradually over time but did not reach the levels seen with the thick tool. This result indicates that thin tools produce less PM. Finally, this research has practical implications for air quality management. Both PM2.5 and PM10 concentrations remained low when the thin tool was used in conjunction with an air suction system. In Fig. 8-D, PM10 and PM2.5 concentrations were measured at around 80 μg/m^3, while the PM2.5 concentration decreased to 72 μg/m^3. These data demonstrate the practical effectiveness of thin tools and air suction systems in reducing PM emissions in indoor environments, a finding directly relevant to air quality management.

3.1.3 Emission measurements during the sapelli process

In the operations performed with Sapelli and under different scenario conditions, the emission measurement results are presented in Fig. 9.

When Fig. 9 is examined, it can be seen that the PM concentration varies according to the type of cutting tool and the condition of the air suction system. In the case where the air

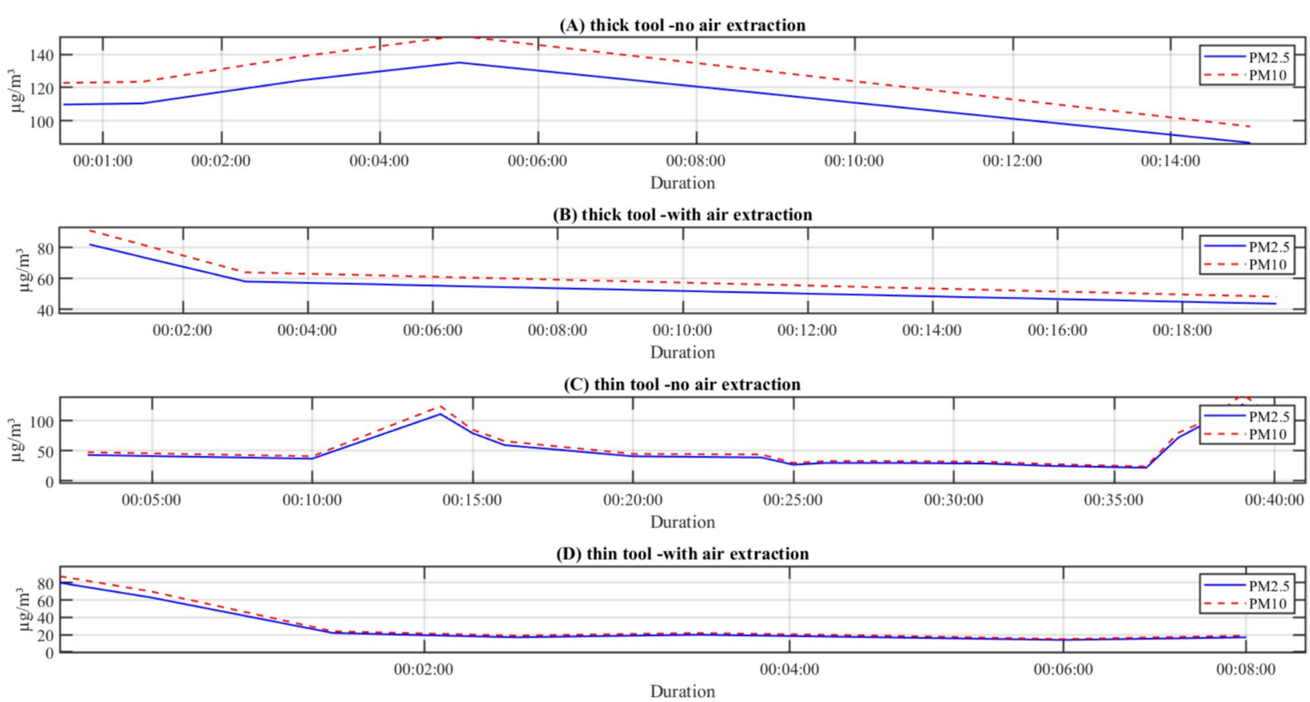

Fig. 9 PM2.5 and PM10 concentration measurement results for different scenarios during sapelli processing

intake system is switched off (Fig. 9-A), a gradual increase in both PM2.5 and PM10 concentrations is observed during the use of the thick tool. The PM2.5 concentration initially increased from 109.8 μg/m^3 to 135.0 μg/m^3 and then gradually decreased when the air intake system was activated (Fig. 9-B). However, the PM10 concentration, which was initially at 122.8 μg/m^3, showed a continuous upward trend, increasing to 151.0 μg/m^3. The persistent increase in PM10 concentration underscores the ongoing issue of air quality deterioration due to the use of thick tools and inactive air suction systems.

A significant decrease in PM2.5 and PM10 concentrations was observed when the air intake system was activated (Fig. 9-B). The PM2.5 concentration decreased from 82.1 μg/m^3 to 53.6 μg/m^3, and the PM10 concentration decreased from 91.2 μg/m^3 to 59.2 μg/m^3. The air suction system effectively controls the high PM levels that arise when using thick tools. During operations using the fine tool, PM2.5 and PM10 concentrations remained relatively low, even when the air intake system was switched off. The PM2.5 concentration decreased from 43.1 μg/m^3 in the first measurement to 39.5 μg/m^3; the PM10 concentration decreased from 47.7 μg/m^3 to 44.1 μg/m^3. The thin tool, with its ability to generate less PM emissions than the thick tool, plays a significant role in maintaining low particle levels in the environment, even when the air suction system is not in operation. It was observed that both PM2.5 and PM10 concentrations decreased to their minimum levels during operations with the fine tool, when the air intake system was on. The PM2.5 concentration decreased from 22.0 μg/m^3 to 14.0 μg/m^3, the PM10 concentration decreased from 24.0 μg/m^3 to 15.0 μg/m^3. The combination of the thin tool and the air suction system effectively removed particles from the ambient air by achieving the lowest PM concentration.

3.1.4 Emission measurements during the chestnut processing

The emission measurement results for the chestnut wood under different scenario conditions are presented in Fig. 10.

In the initial measurements, when the air suction system was turned off and a thick tool was used, the PM2.5 and PM10 levels rapidly increased (Fig. 10-A). For example, the PM2.5 concentration increased from 24 μg/m^3 to 378 μg/m^3, and the PM10 concentration increased from 26 μg/m^3 to 423 μg/m^3. The data show a significant accumulation of PM, especially since PM10 levels are increasing more rapidly. This indicates that a severe indoor air quality problem arises when a thick tool turns off the air extraction system.

With the air intake system switched off, the highest recorded concentrations were 724 μg/m^3 for PM2.5 and 810 μg/m^3 for PM10, indicating that indoor particle accumulation reaches critical levels. Significant reductions in PM2.5 and PM10 levels were observed when the air intake system was activated. The PM2.5 concentration decreased from 95 μg/m^3 to 18 μg/m^3, and the PM10 concentration decreased from 106 μg/m^3 to 20 μg/m^3. When the air intake system is operational, PM levels are quickly controlled

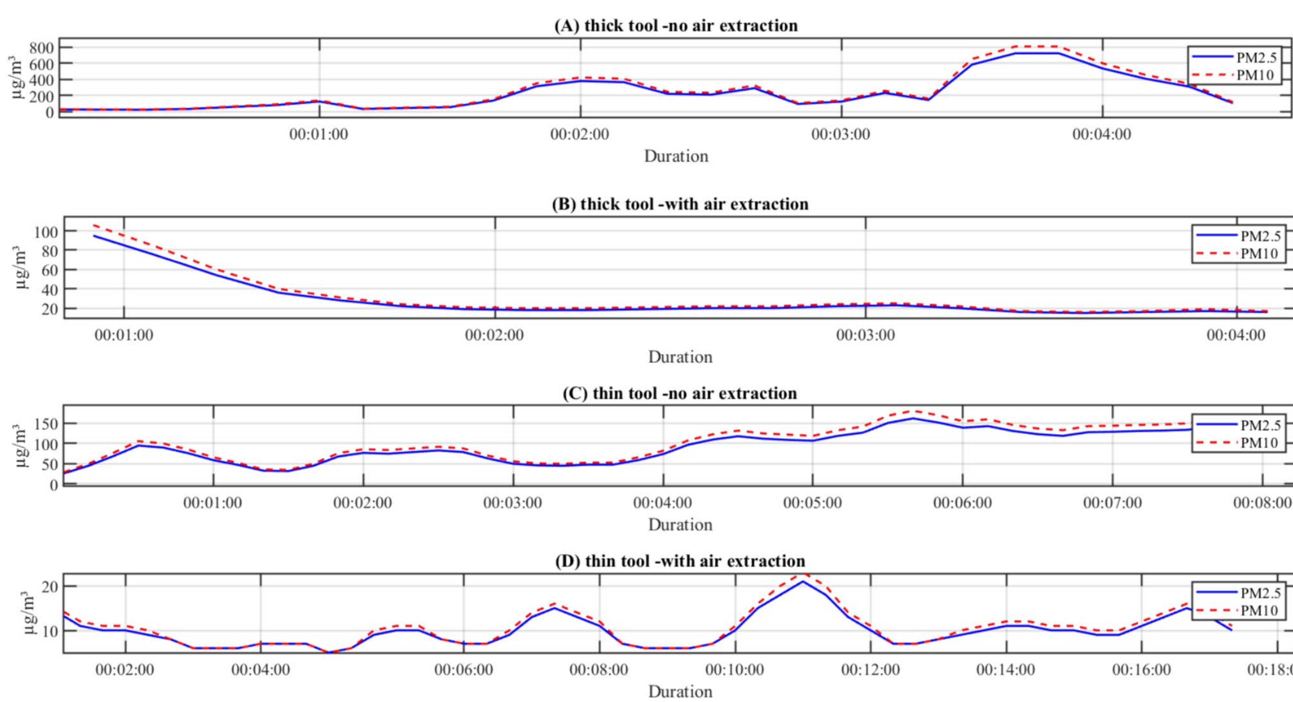

Fig. 10 PM2.5 and PM10 concentration measurement results for different scenarios during chestnut processing

during the operations performed using the thick tool. Significantly, there was a dramatic decrease in the PM10 concentration, demonstrating the air suction system's capacity to effectively remove particles from the environment. During operations using the thin tool, significant increases in both PM2.5 and PM10 levels were observed when the air intake system was switched off. The PM2.5 concentration increased from 26 µg/m^3 to 118 µg/m^3 within the first few minutes. Similarly, the PM10 concentration increased from 29 µg/m^3 to 150 µg/m^3. The thin tool, when used with the air suction system off, showed lower PM levels than the thick tool, providing a clear comparison of their impact. However, accumulation in the environment reached significant levels. The lowest PM2.5 and PM10 levels were observed during operations with the thin tool when the air intake system was switched on. Although the PM2.5 concentration decreased to 14 µg/m^3, the PM10 level also decreased to 15 µg/m^3.

3.1.5 Emission measurements in spruce-based processes

Figure 11 presents the emission measurement results for the spruce wood under different scenario conditions.

The initial measurement values started at 9 µg/m^3 for PM2.5 and 10 µg/m^3 for PM10 (Fig. 11-A). As time progresses, a rapid increase in PM levels is observed when the air suction system is turned off while using the thick tool. For example, the PM2.5 concentration rose to 64 µg/m^3 and the PM10 concentration to 71 µg/m^3 (Fig. 11-A). For example, the PM2.5 concentration increased to 64 µg/m^3, and the PM10 concentration rose to 71 µg/m^3. This increase further accelerated, reaching 293 µg/m^3 for PM2.5 and 328 µg/m^3 for PM10. Subsequently, the PM2.5 concentration peaked at 358 µg/m^3, while the PM10 concentration reached 400 µg/m^3. However, a significant decrease in both PM2.5 and PM10 was observed afterward (Fig. 11-B), emphasizing the effective role of the air intake system in reducing PM levels.

The PM2.5 concentration decreased to 28 µg/m^3, and the PM10 concentration decreased to 31 µg/m^3. When the air intake system was switched on, the accumulated PM decreased rapidly, and the PM2.5 concentration stabilized at 15 µg/m^3, while the PM10 concentration stabilized at 16 µg/m^3. When the air intake system was switched off (Fig. 11-C), PM2.5 and PM10 concentrations remained at lower levels.

The initial PM2.5 level was 9 µg/m^3, while the initial PM10 level was 10 µg/m^3. Over time, the PM2.5 concentration reached a maximum of 18 µg/m^3, while the PM10 concentration peaked at 20 µg/m^3. Compared to the thick tool, less PM accumulation was observed. However, since the air intake system was turned off, particulate accumulation occurred in the environment. When the thin tool was used in combination with the air intake system, PM levels remained relatively low. The PM2.5 concentration stabilized at 12 µg/m^3, while the PM10 concentration stabilized at 13 µg/m^3. A temporary increase in PM2.5 and PM10 concentrations

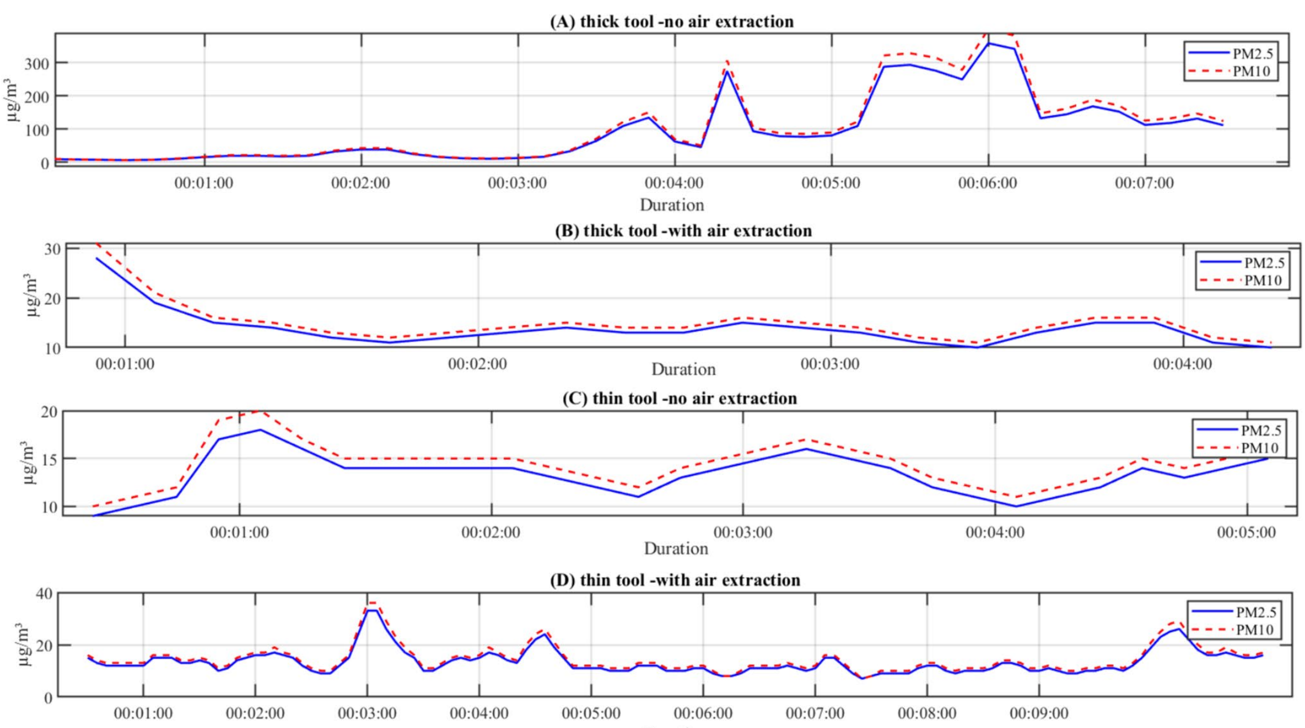

Fig. 11 PM2.5 and PM10 concentration measurement results for different scenarios during the processing of spruce

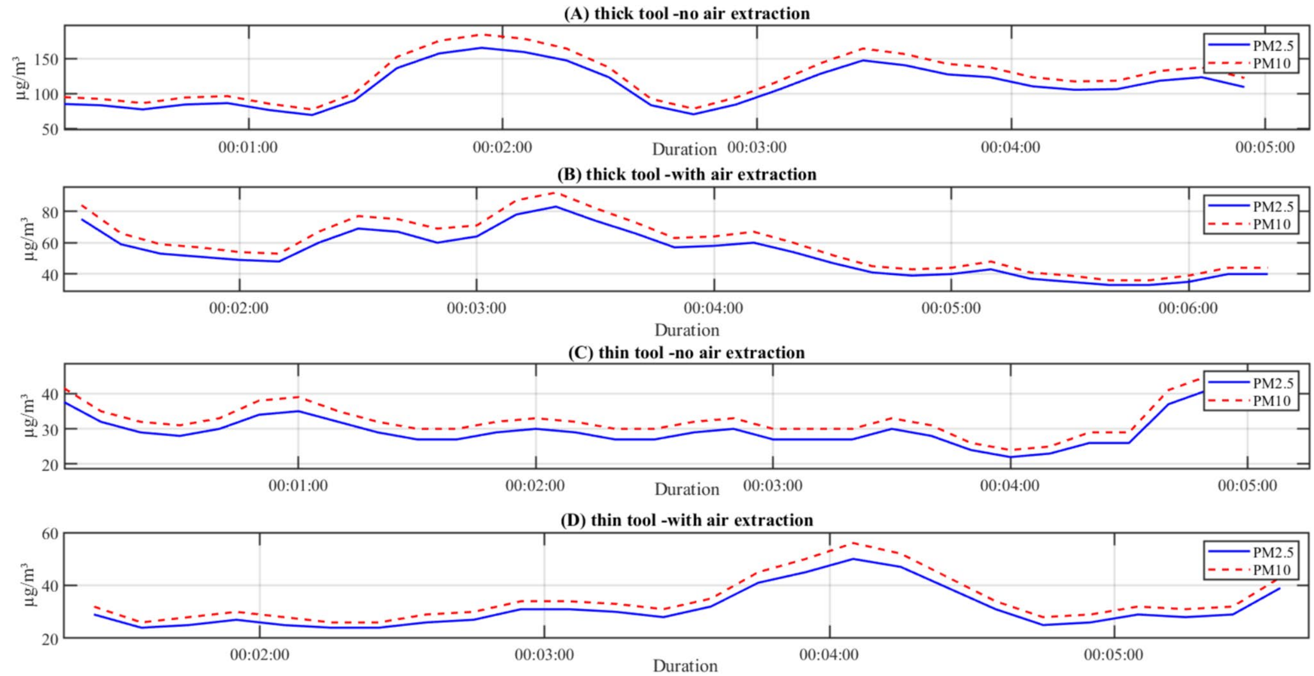

Fig. 12 PM2.5 and PM10 concentration measurement results for different beech processing scenarios

was then observed (PM2.5: 24 μg/m^3, PM10: 26 μg/m^3), but this increase was quickly brought under control (Fig. 11-D).

3.1.6 Emission measurements in beech processing

Figure 12 presents the emission measurement results of the operations performed on beech wood under different scenario conditions.

When the thick tool was used, the PM levels rapidly increased with the air suction system turned off, and the PM2.5 concentration reached 157 μg/m^3, while the PM10 concentration reached 175 μg/m^3 (Fig. 12). However, activation of the air suction system caused an immediate and significant decrease at these levels, with PM concentrations dropping to 75 μg/m^3 (PM2.5) and 84 μg/m^3 (PM10). The immediate impact of the suction system in controlling PM levels was impressive and demonstrated its efficiency. Similarly, during the use of the thin tool, lower PM accumulation was observed when the air suction system was turned off, with PM2.5 and PM10 levels starting at 38 μg/m^3 and PM10 at 42 μg/m^3. Yet, activation of the air intake system quickly decreased these PM levels, further emphasizing its immediate impact on reducing PM accumulation. When the thin tool and air suction system were used, PM levels dropped to the lowest values, and PM2.5 and PM10 concentrations consistently remained low, further highlighting the system's efficiency.

This study revealed the effects of the cutting tool used in CNC machines and the air suction system on the accumulation of PM2.5 and PM10 in the environment. During processing of Sapelli, Chestnut, Spruce, and Beech woods, when the air suction system was turned off, rapid and significant increases in PM levels were observed, especially with the use of thick tools. Compared with the thick tool, the thin tool resulted in lower PM formation levels, but a particular accumulation still occurred when the air intake system was closed. When the air suction system was open, a significant reduction in the PM concentration was observed for both types of cutting edges. The combination of a thin tool and an air suction system has reduced PM accumulation to the lowest levels and is emerging as the most effective solution for maintaining air quality. These results indicate that the continuous use of the air-extraction system during CNC operations is critically important for maintaining the air quality.

3.2 Comparison of PM emissions in different wood species and CNC-processed scenarios

The average emissions produced during the process for each wood species were calculated, and the results are presented in Fig. 13. Additionally, CNC operations were carried out under different scenarios, and the PM2.5 and PM10 emissions generated during these processes were examined. The data obtained from the experiments were subjected to statistical analyses to determine whether there is a significant difference between wood species and processing conditions. The Kruskal–Wallis test was applied to determine general

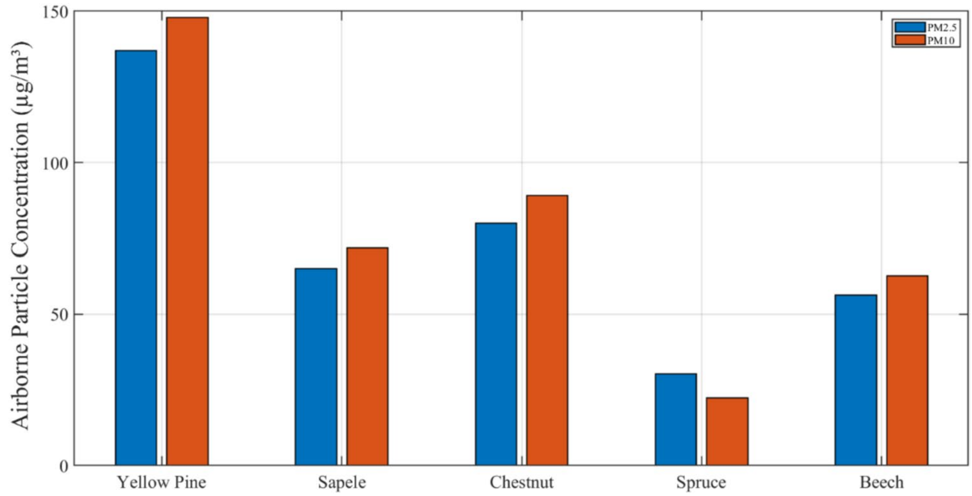

Fig. 13 Average emissions generated during processing by each wood species

differences between groups, and then the Dunn test was conducted to identify differences between scenarios.

Figure 13 shows the average PM2.5 and PM10 emissions from five different species of wood processed on CNC machines. Yellow pine woods have the highest PM2.5 and PM10 emissions. The PM2.5 value of Yellow pine has been measured at 137.07 μg/m^3 and the PM10 value at 147.96 μg/m^3. This indicates that Yellow pine woods produce more PM during CNC processing than other wood species. Sapelli has shown moderate emissions with 65 μg/m^3 values for PM2.5 and 71.79 μg/m^3 for PM10. Conversely, Chestnut has relatively high PM2.5 and PM10 levels of 79.97 μg/m^3

Table 1 Comparison of different wood species in the CNC process according to PM2.5 and PM10 emissions under Scenario 1 conditions

PM2.5		
Test	Wood Species	χ^2; p values
Kruskal–Wallis	Yellow Pine, Sapelli, Chestnut, Spruce, and Beech	$\chi^2 = 236.64$, $p < 0.001$
Dunn Test	Yellow Pine vs. Sapelli	$p = 0.4819$
	Yellow Pine vs. Chestnut	$p < 0.001$
	Yellow Pine vs. Spruce	$p < 0.001$
	Yellow Pine vs. Beech	$p = 0.3124$
	Sapelli vs. Chestnut	$p < 0.001$
	Sapelli vs. Spruce	$p < 0.001$
	Sapelli vs. Beech	$p = 1.0$
	Chestnut vs. Spruce	$p < 0.001$
	Chestnut vs. Beech	$p = 0.0137$
PM10		
Test	Wood Species	χ^2; p values
Kruskal–Wallis	Yellow Pine, Sapelli, Chestnut, Spruce, and Beech	$\chi^2 = 236.67$, $p < 0.001$
Dunn Test	Yellow Pine vs. Sapelli	$p = 0.4705$
	Yellow Pine vs. Chestnut	$p < 0.001$
	Yellow Pine vs. Spruce	$p < 0.001$
	Yellow Pine vs. Beech	$p = 0.3121$
	Sapelli vs. Chestnut	$p = 0.0020$;
	Sapelli vs. Spruce	$p < 0.001$
	Sapelli vs. Beech	$p = 1.0$
	Chestnut vs. Spruce	$p < 0.001$
	Chestnut vs. Beech	$p = 0.0138$
	Spruce vs. Beech	$p < 0.001$

and a PM10 value of 89.09 μg/m^3. This indicates that the chestnut wood emits more PM than the sapelli wood. On the other hand, the spruce has the lowest emission value among all wood species. The PM2.5 value has been measured at 30.21 μg/m^3 and the PM10 value at 22.38 μg/m^3. This shows that spruce is the species of wood that produces the most minor PM during CNC processing. The beech wood, on the other hand, has shown moderate emissions, with values of 56.35 μg/m^3 for PM2.5 and 62.64 μg/m^3 for PM10. While having lower emissions than sapelli, produce beech produces more PM.

In the CNC processing, comparisons of different species of wood according to PM2.5 and PM10 emissions under Scenario 1 conditions are presented in Table 1. The Kruskal–Wallis test revealed significant differences in PM2.5 emissions produced by different wood species during CNC processing ($\chi^2 = 236.64$, $p < 0.001$). This indicates that each wood species produces different amounts of PM2.5. The Dunn test results revealed a significant difference in PM2.5 emissions, particularly between Yellow Pine and Spruce. It was found that Spruce emits significantly less PM2.5 than Yellow Pine ($p < 0.001$). Similarly, significant differences were noted between Yellow Pine and Chestnut. Yellow Pine was found to produce the highest PM2.5 emissions, while Spruce had the lowest emissions. These findings have important practical implications because they underscore the substantial influence of wood species on PM emissions in CNC machining and can guide industry practices toward more sustainable choices.

According to the results of the Kruskal–Wallis test in Table 1, a significant difference was found in PM10 emissions among wood species ($\chi^2 = 236.67$, $p < 0.001$). This shows that different species of wood produce different levels of PM10 emissions during the CNC process. The difference in PM10 between Yellow pine and spruce was significant ($p < 0.001$), indicating that Spruce produces significantly lower PM10 emissions than Yellow Pine. Similarly, the difference between Yellow pine and chestnut was also significant ($p < 0.001$). Significant differences were also detected between Sapelli and Chestnut ($p < 0.01$), indicating that these two wood species produce different levels of PM10 emissions during CNC processing. In contrast, no significant differences were found between Yellow pine, sapelli, and beech woods ($p > 0.05$), indicating that these wood species have similar PM10 emission levels. Additionally, the difference between Chestnut and Beech was significant ($p < 0.05$), indicating that Chestnut produces more PM10 than Beech.

In conclusion, there were significant differences in PM10 emissions produced by different wood species during the CNC process. Spruce has the lowest PM10 emissions, while Yellow pine produces the highest. These findings indicate that the selection of wood species during the CNC process significantly affects the emission of environmental PM. The statistical evaluation of the differences among the CNC machining scenarios is presented in Table 2.

The statistical analyses in the scenarios (Table 2) also revealed significant differences in PM2.5 and PM10 emissions among the wood species. According to the results of the Kruskal–Wallis test, significant differences were detected in all scenarios ($p < 0.001$). The Dunn test results show that Yellow Pine has higher emission values than other wood species, such as Spruce, Chestnut, and Beech. The difference between Yellow Pine and Spruce is statistically significant in most scenarios, indicating that spruce produces lower PM2.5 and PM10 emissions during CNC processing. Additionally, no significant differences were observed between Sapelli and other wood species in specific scenarios, indicating that Sapelli's emission performance was moderate. Significant differences were observed between chestnut, spruce, and beech, with spruce having the lowest emission values. These results

Table 2 Significant differences in PM2.5 and PM10 emissions among wood species in different CNC machining scenarios

Scenario	(p)	Dunn Test Results
Scenario 2	$p < 0.001$	Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Yellow Pine vs. Beech, Chestnut vs. Spruce
Scenario 3		Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Yellow Pine vs. Beech, Chestnut vs. Beech
Scenario 4		Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Sapelli vs. Chestnut, Sapelli vs. Spruce, Chestnut vs. Spruce, Chestnut vs. Beech, Spruce vs. Beech
Scenario 5		Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Sapelli vs. Spruce; Chestnut vs. Spruce; Chestnut vs. Beech, Spruce vs. Beech
Scenario 6		Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Yellow Pine vs. Beech, Chestnut vs. Spruce
Scenario 7		Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Yellow Pine vs. Beech, Chestnut vs. Spruce, Chestnut vs. Beech, Spruce vs. Beech
Scenario 8		Yellow Pine vs. Sapelli, Yellow Pine vs. Chestnut, Yellow Pine vs. Spruce, Sapelli vs. Chestnut, Sapelli vs. Spruce, Chestnut vs. Spruce, Chestnut vs. Beech, Spruce vs. Beech
Scenario 9		Yellow Pine vs. Chestnut: Yellow Pine vs. Spruce, Sapelli vs. Spruce; Chestnut vs. Spruce; Chestnut vs. Beech, Spruce vs. Beech

indicate that the species of wood used in CNC operations significantly impact PM emissions and that spruce is an advantageous option for emission control.

In the study, among the deciduous wood species, the beech samples emitted lower dust emissions than the chestnut and capelli samples, which is similar to the finding of Pędzik et al. (2021) in their research on sandpaper particle sizes, where beech samples formed particles with the most minor diameter. As shown by Sydor et al. (2022), processing parameters and wood species affect fine dust generation, which can be harmful to health. The results of the study by Juda et al. (2023) also confirm our findings, demonstrating that wood species significantly influences dust particle size distribution during milling.

As a result of the study, Yellow Pine was identified as the wood species with the highest PM concentration in the air. In contrast, the samples from the Spruce, which are another coniferous wood species, were measured to have the lowest PM concentration. Examples of deciduous wood species are ranked between these two species. It is thought that this difference in dust concentration between the Yellow Pine and Spruce samples is due to differences in the microscopic characteristics of the wood species. These two wood species show similarities in essential density, shrinkage, and swelling rates as well as ratios of holocellulose, cellulose, and lignin. However, it has been reported that the Brinell hardness and compressive strength of Yellow Pine wood are higher than those of Spruce wood (As et al. 2001).

Furthermore, it is crucial to note that the Runkel ratio, a key determinant of the suitability of a wood species for paper production, is higher in Yellow Pine samples (Bozkurt et al. 1991). The Runkel ratio, defined as twice the fiber wall thickness divided by the lumen width, is ideally less than 1 for efficient paper production (Kılıç et al. 2017). Based on these differences, it can be concluded that coniferous wood species with high pressure, hardness, and Runkel values create a higher concentration of dust when processed on CNC machines.

According to this result, there was a positive correlation between the dust concentration rates of the wood species and their hardness and Runkel values. After this study, it is recommended that research be conducted to determine the relationship between the dust concentrations of wood species and their hardness and Runkel values. However, machining can also be performed by selecting different spindle speeds, cutting speeds, and feed rates for different species of wood and milling cutter diameters according to CNC parameters. In the industry, valuable options for complex processing parameters can also be offered. In addition, artificial neural network prediction methods can also be used.

4 Conclusion

This study analyzed the emission values of five different wood species during CNC operations performed with the same spindle speed, cutting speed, feed rate, and two different cutters. Among the wood species analyzed, Yellow pine exhibited the highest emission values, followed by chestnut, while larch produced the lowest emissions. Sapelli's emissions were at medium levels, and beech ranked fourth in emission levels. These results reveal significant differences in the environmental and occupational health impacts of wood species used in CNC operations.

The findings indicate that Yellow pine, characterized by its high Brinell hardness and dense fiber structure, generates significantly more dust during CNC operations, leading to elevated PM concentrations in the workplace. In contrast, spruce, with its lower hardness and density, produces lower emission levels, making it a more suitable option for maintaining air quality in CNC machining environments. These results highlight the critical role of wood species' microscopic and structural properties in influencing emission levels.

Another key finding of this study is the impact of cutter diameter and type on emission levels. Fine cutting edges combined with effective air suction systems significantly reduce PM2.5 and PM10 levels, ensuring safer air quality in the workplace. This study underscores the importance of selecting fine-cutting tools and integrating advanced dust extraction systems to control emissions during CNC machining processes. Such measures play a pivotal role in protecting worker health and minimizing the environmental impact of high-emission wood species.

From the perspectives of occupational health, safety, and environmental sustainability, this study highlights the necessity of careful material and equipment selection in CNC machining processes. For high-emission wood species, it is essential to develop more efficient dust extraction systems, utilize fine-cutting tools, and optimize CNC parameters to minimize emissions and reduce worker exposure risks. Future research should further investigate the relationship between wood species' mechanical properties, such as Brinell hardness and Runkel ratio, and their emission levels during CNC machining. These studies will provide valuable insights into selecting lower-emission materials and promoting sustainable practices in the woodworking industry.

In conclusion, the species of wood and cutting tool used are significant variables affecting air quality during CNC operations. Strategic approaches, including the preference for low-emission wood species and the development of advanced dust control technologies, are vital for improving occupational health and safety. These efforts not only protect worker health but also contribute to reducing the environmental footprint of the CNC machining industry, offering a promising outlook for its sustainable future.

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Declarations

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