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Posted Date: 28 November 2023

doi: 10.20944/preprints202311.1786.v1

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Assessing the Impact of Saw Chain Type and Wood Species on Wood Dust Concentration in Forestry Operations: Implications for Air Pollution in Urban and Industrial Areas

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Abstract: This study examines the impact of chainsaw chain type and tree species on the concentration of inhalable wood dust generated during motor-manual harvesting in forested areas. The chainsaw chain is a critical component, contributing not only to productivity but also to the operator's health and safety. Wood dust creation during harvesting operations poses significant risks and necessitates careful attention due to its potential health effects. We investigated the effects by conducting real-world measurements of inhalable dust within the operator's breathing zone during forestry work. Two different chain types were evaluated: the commonly used 3/8" pitch chain (conventional chain) and the 0.325" pitch chain. Additionally, measurements were taken for three tree species: beech, oak, and pine (including both live and standing dead trees after a fire). Results showed that, overall, using the conventional 3/8" chain type yielded the highest concentration of wood dust for all three tree species. Notably, the highest wood dust concentration was observed in the burned *Pinus brutia* cluster, also with the 3/8" chain pitch. These findings emphasize the importance of understanding how chain type and tree species contribute to wood dust levels and provide valuable insights for enhancing operator health and safety during motor-manual harvesting operations.

Keywords: chainsaw chain type; inhalable wood dust concentration; motor-manual harvesting; operator health and safety; tree species

1. Introduction

The introduction of fully mechanized wood harvesting is unfeasible in several countries, at least for now, due to steep terrain, fragmentation of ownership, and environmentally-friendly forest management practices (close-to-nature management). As a result, motor-manual harvesting remains the dominant method of wood harvesting for many countries (Southeastern Europe, Asia, Asia Africa) [1, 2, 3, 4]. The advantages of chainsaw use include low investment cost and the flexibility of its use, as it is the only motorized tool allowed to be used within the forest [5, 6, 7]. Additionally, gasoline-powered chainsaws have seen a slow but steady increase in their performance by increasing engine power and speed control [8]. This means that higher performance contributes to a reduction in energy consumption for the production of one unit of goods. According to [9], increased productivity reduces greenhouse gas emissions, which are the main cause of climate change.

However, chainsaw use has its drawbacks, including noise, vibrations, physical strain, exhaust gases, and airborne wood dust [10]. Several researchers have examined the problems associated with noise [11, 12, 13], vibrations [14, 15, 16], physical strain [17, 18, 19], as well as the determination of carbon monoxide [20, 21], and exhaust emissions [22, 23, 24].

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Regarding the concentration of airborne wood dust in real working conditions during harvesting in a forest, fewer researchers have focused on this topic [25, 26], while there is sufficient research on wood dust concentrations in enclosed spaces such as wood industries [27, 28, 29]. However, several researchers emphasize that the occupational exposure limits are based on epidemiological studies from the furniture industry and may not reflect the specific conditions prevailing in outdoor workspaces.

Usually, chainsaw operators do not take into consideration the risk of exposure to airborne wood dust, as they are less aware of its negative health consequences [30]. Nevertheless, the risk is significant, such as the changes it can induce in pulmonary function and allergic respiratory responses (asthma). Moreover, there is a scalable risk of developing cancer, particularly nasal and sinus adenocarcinoma [31, 32]. For this reason, the International Agency for Research on Cancer has classified hardwood dust as carcinogenic [33]. Therefore, there is a relevant directive [34] for the countries of the European Union, which sets the legal exposure limit for inhalable wood dust at 5 mg/m^3 [25]. Meanwhile, there is a continuous trend of reducing this limit. In 2017, with [35], the occupational exposure limit (OEL) was reduced to 3 mg/m^3 until January 17, 2023, and later to 2 mg/m^3.

The chain is one of the essential parts of a chainsaw, and the correct selection of the chain affects important factors such as cutting efficiency, safety, and ergonomic suitability of the chainsaw [8]. However, it is observed that while there is technical data available for the correct selection of a chainsaw chain in relation to the chainsaw, there is a lack of quality data for making rational decisions in choosing a chainsaw chain [8]. A literature review revealed the need for a new comprehensive analysis of the risks associated with the use of internal combustion portable chainsaws [36]. [8] emphasize that assessing the effectiveness of the most relevant technical solutions used today in portable chainsaws to protect operators' health from inhaled dust during work is of great importance.

The objective of this study was to determine the factors that affect the performance and concentration of inhalable wood dust produced using chains of different pitches. In chainsaws, the chain pitch refers to the distance between three consecutive rivets divided by two (Figure 1). It is a measurement that determines the compatibility between the chain and the guide bar on the chainsaw. The chain pitch represents the size of the chain, specifically the spacing between the drive links that engage with the sprocket and guide bar, and it is usually measured in inches. The correct chain pitch must match the corresponding sprocket and guide bar to ensure proper functioning and optimal cutting performance of the chainsaw. Chains with different pitches are not compatible with one another, as their drive links will not align or engage correctly with the sprocket and guide bar. A typical chainsaw chain has a pitch of 3/8" (9.5 mm) [37]. Specifically, the study considered: (i) two types of chains with different pitches from the same producer, (ii) three tree species, and (iii) healthy standing and dead trees. It should be noted that this research effort is part three of a larger research project, with part two focusing on the operating conditions of chainsaws in terms of maintenance [38], and part one on tree dimensions and tree species [39].

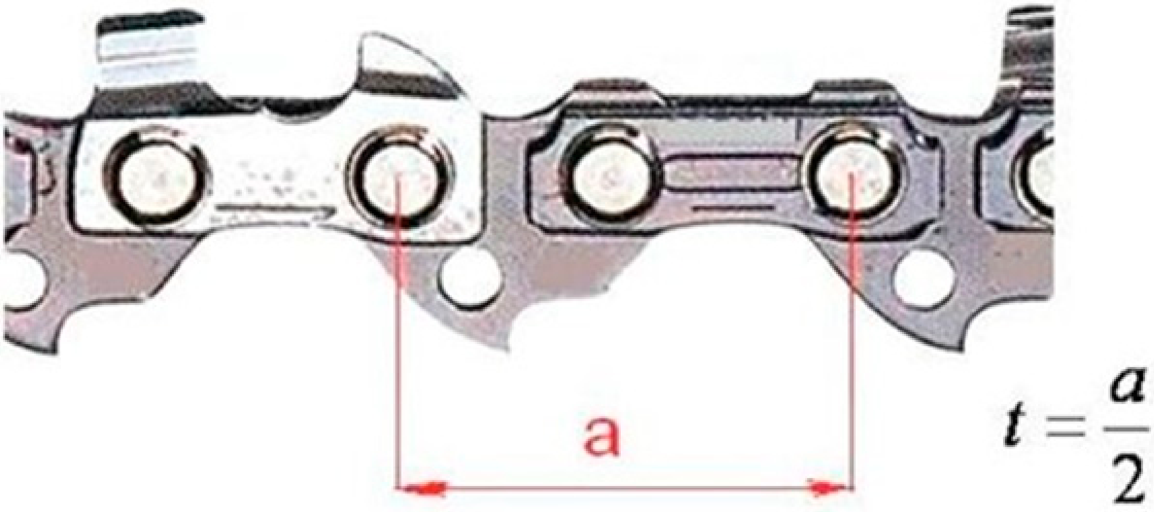

Figure 1. Determination of chain pitch, where a: distance between three rivets, and t: chain pitch equal to half the distance between the axes of three rivets.

2. Materials and Methods

2.1. Wood dust concentration measurement

In real wood harvesting conditions, experimental measurements were conducted to assess inhalable wood dust. To capture the wood dust, a Sample Conditioning for Kiln (SCK) air sampling device, equipped with an IOM (Institute of Occupational Medicine) type sampler and a binder-free GFA filter (25 mm glass fiber filter) was utilized. The airflow velocity at the sampling point was maintained using a Button Sampler (Sidekich, flow scale 5-3000ml/min) connected to the IOM sampler through a tygon tube. The SCK Button Sampler was set to operate at a flow rate of 4l/min [25, 39]. Prior to each sampling session, the portable pump was calibrated using a field rotameter (range 400 ml - 5l/min). Each sampling session, lasting approximately 6 hours per day, took place in the operator's breathing zone during their work in the forest. For each new sampling session (corresponding to a different working day), a fresh filter was placed inside the cassette of the IOM sampler after preconditioning the filters for a minimum of 24 hours in a climatic chamber set at 20 ± 1°C temperature and 48 ± 2% humidity. Wood dust calculation was performed through the gravimetric method, weighing the filters on a precision balance (ADAM NBL 164e) before and after their use [40].

2.2. Chainsaw chain types

The experiment utilized two chain types: a 3/8" chain and a 0.325" chain, differing in the distance between three rivets. The 3/8" pitch chain has a rivet distance of t = 19.2 mm, while the 0.325" pitch chain has a rivet distance of t = 16.7 mm (Figure 2). Both chain types were technically suitable for the chainsaws employed in the study. Specifically, chainsaws from the same manufacturer, namely Husqvarna 55 and Husqvarna 562XP, were utilized. These chainsaws shared comparable power and engine sizes, with power ratings of 53.2 and 59.8 kW and engine sizes of 2.5 and 3.5 cm3, respectively.

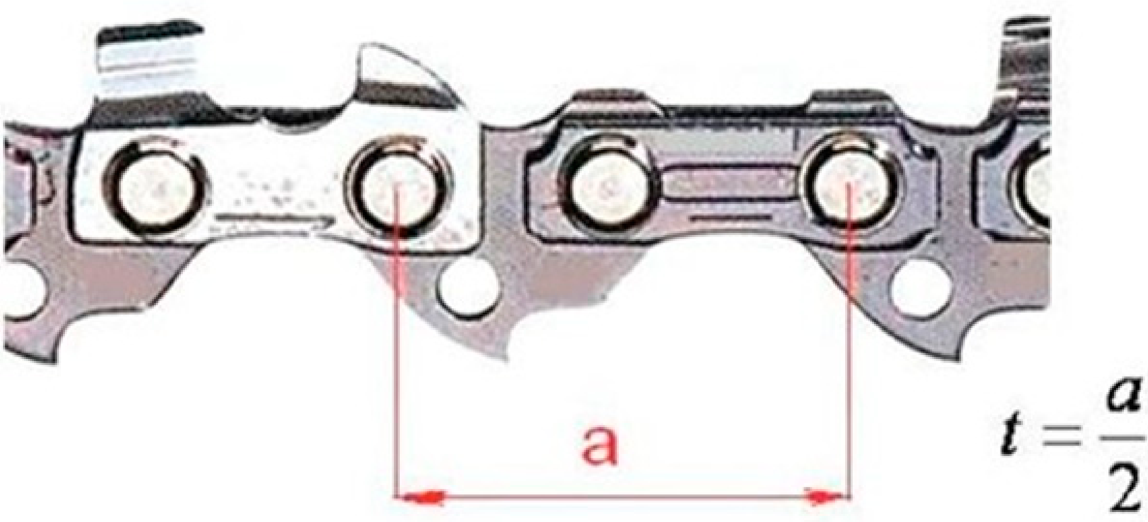

Figure 2. Pitch of the 3/8" and 0.325" chains.

2.3. Test specimens

The study examined three tree species: beech (*Fagus sylvatica* L.), oak (*Quercus petraea*), and pine (*Pinus brutia* Ten.). Measurements of dust concentration were conducted in both healthy standing trees and standing dead pine trees following a fire incident. A total of 96 sampling measurements were taken, with each chain type and tree species undergoing 12 repeated measurements over 12 working days (Table 1).

Table 1. Main characteristics of the sampling sites.

Chain Type	Coding	No of Processed Trees	Average DBH[5] (cm)	Number of Samples
Pitch Chain 3/8″	3/8″*Fs*[1]	45	60.48	12
	3/8″*Qp*[2]	91	38.57	12
	3/8″*Pbr*[3]	256	30.78	12
	3/8″*Pbr.bur*[4]	296	28.43	12
Pitch Chain 0.325″	0.325″*Fs*	80	53.01	12
	0.325″*Qp*	184	38.96	12
	0.325″*Pbr*	460	32.21	12
	0.325″*Pbr.bur*	495	29.36	12

1: *Fagus sylvatica*, 2: *Quercus petraea*, 3: *Pinus brutia*, 4: *P. brutia burned*, 5: Diameter at Breast Height

2.4. Timing of work tasks

During the sampling period, consistent procedures were followed to ensure reliable results. A skilled operator with relevant work experience performed all the sampling activities, having received prior instructions and provided necessary consent. To account for any potential variation in work methods, the duration of work was meticulously recorded for the operator's entire daily activities and throughout the sampling period. As wood dust generation primarily occurs during chainsaw movement (excluding engine idling), the work time was categorized into two phases: a) with the chainsaw engine in motion (cutting, delimbing, and bucking) and b) with the chainsaw engine not in motion (work-related delays and idling phases) [24, 26, 41]. Continuous timing measurements were employed to determine the duration of each work phase accurately, calculated as the difference between the end time of the previous work phase and the end time of the subsequent work phase.

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Furthermore, before each tree felling event, the breast height diameter and tree species were measured and recorded. The wood dust concentration measurements were derived from a wide range of tree felling instances and configurations, specifically from a total of 1907 cases. Among these, 688 cases involved the use of the 3/8" chain, while the remaining 1219 cases involved the use of the 0.325" chain [39].

2.5. Statistical methodology

The two proportion z-test [42, 43, 44] was used to determine whether there are statistically significant differences between chain types in terms of work phases (preparation time, total time on site, chainsaw running, delays), and wood dust concentration.

3. Results

3.1. Resutls of work tasks

Table 2 presents the breakdown of work time distribution for the two chain types used. The total work time on site amounted to 33,092.66 minutes (equivalent to approximately 551 hours), with an average daily work time of around 6 hours. Specifically, for the chainsaw equipped with a 3/8" chain and a 0.325" chain, the net work time was 226.73 minutes and 244.48 minutes, respectively, accounting for 67.60% and 68.88% of the total work time for each chain type. Work phases where the chainsaw engine was not in motion, including preparation time (20.35 and 20.84 minutes) and delays (88.26 and 88.77 minutes), accounted for 31.50% and 31.79% of the total work time (total time on site) for the respective chain types.

Table 2. Work time distribution per work phase.

Chain type	Mean preparation time (minutes)	Total time on-site (minutes)	Mean chainsaw running time (minutes)	Mean delay (minutes)	Chainsaw running time as a percentage of total time on-site	Number of samples
Pitch Chain 3/8″	20.35	335.33	226.73	88.26	67.60	48
Pitch Chain 0.325″	20.84	354.10	244.48	88.77	68.88	48

Table 3 illustrates the average distribution of work time, highlighting the periods when the chainsaw engine is actively in motion and the breakdown by work task (felling, limbing, bucking) concerning the chain type. Each column depicts the chainsaw work time per work task (in minutes and as a percentage of the mean chainsaw running time). The two proportion z-test resulted in a significantly increased felling (z=-2.589, p-value=0.010) and limbing (z=-3.749, p-value=0.000) time for the 0.325" chain, while the bucking time was significantly decreased for the 0.325" chain (z=4.793, p-value=0.000). The penultimate column of Table 3 displays the average DBH of the harvested trees for each chain type (3/8" and 0.325").

Table 3. Daily average running time per work task.

Chain type	Mean felling time (minutes, %)	Mean limbing time (minutes, %)	Mean bucking time (minutes, %)	No of processed trees	Average DBH (cm)
Pitch Chain 3/8″	8.44 3.72%	32.88 14.50%	185.41 81.78%	688	39.57
Pitch Chain	15.99	52.59	175.91	1219	38.39

0.325″	6.54%	21.51%	71.95%

Figure 3 demonstrates the distribution (%) of the primary time components, emphasizing the percentage of non-motion and motion of the chainsaw in relation to the three examined tree species.

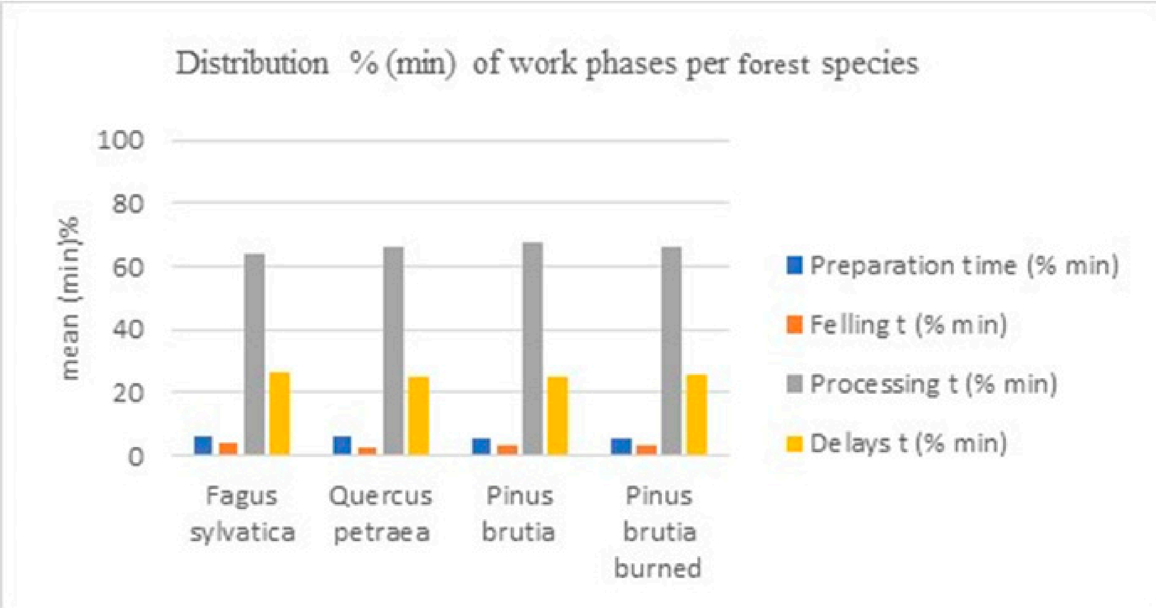

Figure 3. Work time distribution per work phase in relation to forest species.

3.2. Inhalable wood dust concentrations

Table 4 displays the concentration levels of dust based on chain pitch. These measurements reflect the exposure of forest workers to dust concentrations during approximately 6 hours of work. To align with the 8-hour Occupational Exposure Limits (OEL) for wood dust [34], the results have been extrapolated and presented in the fourth column as 8-hour equivalent concentrations. Additionally, the average temperature and humidity measurements of the environment are reported in the last two columns.

The mean dust concentration for the 3/8" chain type was 3.07 mg/m³, while for the 0.325" chain type it was 2.82 mg/m³, resulting in a statistically insignificant decreased concentration for the 0.325" chain (z=0.072, p-value=0.943)). Dust concentration measurements taken on non-working days, but over a 6-hour duration equivalent to the daily mean work time, resulted in a dust concentration of 0.23 mg/m³.

From Table 2 and Figure 3, it becomes evident that the distribution of work time among the work phases for both chain types was nearly identical, indicating that the forestry worker's work method did not significantly impact the wood dust concentration. Instead, the chain type used appeared to be the primary factor influencing the observed wood dust concentration levels. These findings have implications for mitigating air pollution in urban and industrial areas arising from wood harvesting activities.

Table 4. Daily average dust concentration.

Chain type	Mean wood dust concentration (mg/m³)	Min wood dust concentration (mg/m³)	Max wood dust concentration (mg/m³)	Mean wood dust concentration / 8 hours (mg/m³)	Mean humidity (%)	Mean temperature (°C)
Pitch Chain 3/8″	3.07 (±1.62)*	0.61	8.11	4.19	52.28	16.98

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Pitch Chain 0.325″	2.82 (±1.25)	0.87	5.82	3.83	48.24	18.08

* Standard deviation

Figure 4 provides a detailed presentation of inhalable wood dust concentrations, categorized by tree species (including dead pine trees) and chain type. Each measurement involved 12 sampling filters, corresponding to a total of 12 days of sampling (n=12 days). Among healthy standing trees, the highest wood dust concentration was observed in pine using the 3/8" chain pitch (3.03 mg/m^3), whereas the lowest concentration was recorded for the same tree species with the 0.325" chain pitch.

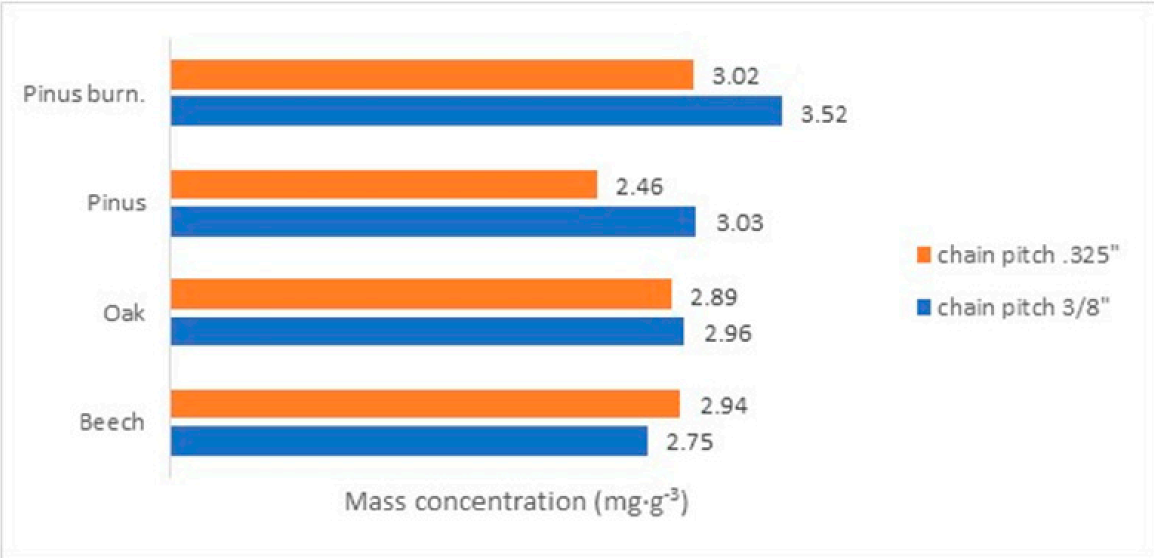

Figure 4. Effect of chain pith (3/8″, 0.325″) and wood species on inhalable dust concentration.

In order to assess the wood dust concentrations relative to the current OEL for wood dust in Greece (OEL = 5 mg/m^3) and considering OELs from other European countries, three concentration classes were established (Table 5). The first class classified filters with wood dust concentrations above 5 mg/m^3 as very high concentrations. The second class included filters with wood dust concentrations between 3 mg/m^3 and 5 mg/m^3 as high concentrations (3,5] mg/m^3. The third class grouped filters with wood dust concentrations at or below 3 mg/m^3 as low concentrations (≤ 3 mg/m^3). The classification of the sampling filters (N) was performed based on tree species and chain pitch (Tables 5 and 6).

Table 5. Number of samples in relation with wood dust concentration classes according to OEL.

Chain type	≤3 mg/m^3	(3,5] mg/m^3	>5 mg/m^3
Pitch Chain 3/8″	26 (54.17%)	16 (33.33%)	6 (12.50%)
Pitch Chain 0.325″	28 (58.00%)	18 (38.00%)	2 (4.17%)

Table 6. Number of sampling filters in the >5 mg/m^3 wood dust concentration, per tree species.

Chain type	Beech	Oak	Pine	Pine burned	Total
Pitch Chain 3/8″	0 (0.00%)	1 (8.33%)	2 (16.67%)	3 (25.00%)	6 (12.50%)
Pitch Chain 0.325″	2 (4.17%)	0 (0%)	0 (0%)	0 (0%)	2 (4.17%)

4. Discussion

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Exposure to wood dust poses respiratory and dermatological risks, including potential carcinogenic effects [45]. Unfortunately, workers often lack awareness regarding the hazards of occupational wood dust exposure, potentially due to adaptation to working conditions and a lack of specific government standards [46]. Current occupational exposure limits for wood dust are based on the wood processing industry and apply to an 8-hour workday without specifically addressing the forestry and logging sector. Furthermore, there is a lack of standardized procedures for measuring wood dust concentration from chainsaws [10].

To address these issues, this study conducted measurements of inhalable wood dust during real harvesting operations within the breathing zone of chainsaw operators. The research aimed to assess the influence of chain pitch, tree species, and the presence of dead standing trees (caused by fire) on airborne wood dust concentrations in timberland. The results show a slight variation in wood dust generation influenced by chain pitch, with mean concentrations of 3.07 mg/m^3 for a 3/8" chain pitch and 2.82 mg/m^3 for a 0.325" chain pitch during a 6-hour work duration (Table 4). Moreover, the sampling indicated a higher percentage (12.50%) of very high wood dust concentrations (>5 mg/m^3) associated with the 3/8" chain pitch. Figure 4 also illustrates that, excluding beech, all other tree species exhibited higher wood dust concentrations with the 3/8" chain pitch. These findings correspond with the work conducted by [47] highlighting risks and increased inhalable dust concentrations during salvage cut operations on dry wood left in the forest for an extended period.

Similar studies conducted by [48, 49, 50] measured wood dust concentrations during the cutting and processing of dead standing trees. They found higher mean concentrations of total wood dust mass and inhalable fractions for oak wood, followed by fir and beech wood [48, 49, 50]. Additionally, [25] evaluated inhalable wood dust exposure in various forest operations, indicating higher mean wood dust concentrations in clear-cut coppice operations compared to silvicultural treatments, particularly focusing on hardwood species (*Quercus cerris* L., *Ostrya carpinifolia* L.).

Table 5 demonstrates an association between wood dust concentration classes (>5 mg/m^3, (3,5] mg/m^3, and ≤ 3 mg/m^3) and mean breast height diameter, with smaller diameters (34.72 cm) corresponding to the very high concentration class. The diameter tends to increase as wood dust concentration decreases, reaching 38.34 cm for the high concentration class and 40.01 cm for the acceptable concentration class. These findings are consistent with previous research highlighting the inverse relationship between wood dust concentration and tree dimensions [39].

Furthermore, Tables 2 and 3 indicate that wood dust concentrations are not influenced by the chainsaw operator's work rate, as consistent work rates were maintained throughout the sampling period, ensuring reliable and accurate results.

5. Conclusions

The safety improvements offered by fully mechanized harvesting operations do not apply to motor-manual harvesting work [51, 52]. Considering that in many countries (Southeastern Europe, Asia, Asia Africa) the chainsaw is the only logging machine used in the forest [1, 2, 3, 4], it is necessary to continuously improve chainsaws to make the work as human-friendly as possible [8]. Due to limited data on wood dust exposure and the lack of clear standards [46] for protecting workers from wood dust exposure, there is significant uncertainty in assessing the risks faced by forest workers.

In this study, it was found that approximately 44% (42 out of 96 sampling filters) of the total sampling filters exceeded the occupational exposure limit that applies to wood dust in most European countries (3 mg/m^3). Furthermore, it was found that the chain pitch affects wood dust levels. Specifically, using a 0.325" chain pitch compared to a 3/8" chain pitch resulted in lower wood dust concentrations overall and for each tree species, except for beech, where there was a small difference that was not statistically significant. Increased wood dust concentrations were observed in tree species with thick bark, such as oak and pine, while the lowest wood dust concentration was observed in beech, which has a relatively high wood density but thin bark. These findings align with a previous study by [26], which allows us to conclude that bark thickness primarily influences wood dust levels. Additionally, an additional conclusion from this research is that the highest wood dust concentrations were found in dead standing Pinus trees.

Taking into account the unique and specialized extracts found in each tree species, the toxicity of fresh wood differs. In this context, pine contains endotoxins and monoterpenes, which make the generated wood dust more hazardous [53, 54]. Therefore, it is not only the quantitative characteristics but also the quality characteristics of fresh wood dust that make it dangerous for workers. In this regard, the existing occupational exposure limits for wood dust should be reconsidered, especially for the forestry sector.

Based on the conclusions of this study, and considering that the chain is one of the essential parts of a chainsaw, it is evident that the type of chain directly affects both work efficiency and the risk to workers' health. While chainsaw manufacturers typically advertise safety features, it is clear that producers need to make complex decisions to optimize chains so that safety goals can be achieved. Nevertheless, more research is needed on the quality characteristics of a chain, rather than just the technical characteristics, to facilitate better and more transparent information about the choice of a chain [8].

Supplementary Materials: Not applicable.

Author Contributions: All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Vasiliki Dimou, Theodora Tioutiuntzi, and Kyriaki Kitikidou. The first draft of the manuscript was written by Vasiliki Dimou and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article. The data presented in this study are available in the tables and figures of this article.

Acknowledgments: The authors wish to express their sincere gratitude for their cooperation with the members of the forest cooperatives in the Prefecture of Derio-Dadia-Loutron, Northeast Greece. This synergy between the forest cooperatives and academia contributed to a great to the implementation of the current research project. We hope that the research will contribute to the existing body of knowledge and raise awareness among forest managers.

Conflicts of Interest: The authors declare no conflict of interest.

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