Reliability of the Measurement Method in Determining the Mass Concentration of Hardwood Dust

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The reliability of the measurement method in determining the mass concentration of wood dust relates to the sampling time for the detection of wood particles in the ambient air of woodworking places. The aim of this study was to calculate the mass limit of detection (LOD), limit of quantification (LOQ), and the minimal sampling time (t_{LOD} and t_{LOQ}) for determination and quantification of samples, based on the hardwood dust mass concentration at various woodworking places in the sawmills, floor production factories, and carpentries. Determination of the mass concentration of respirable, inhalable, and total hardwood dust from ambient air was performed using personal sampling pumps and three types of filter holders: respirable dust cyclone, Institute of Occupational Medicine IOM inhalable dust sampler, and total dust open-faced filter holder. The average limit of detection amounts to 0.052, 0.083, and 0.167 mg for respirable, inhalable, and total hardwood dust, respectively. The minimal detection sampling time for collecting all observed types of dust fractions ranged between 1.12 h and 1.72 h. The minimal quantification time for all collected hardwood dust samples ranged from 3.75 h to 5.51 h. Pearson's correlation test showed that the reliability of the measurements was affected more by the dustiness of the workspace than the real sampling time.

Keywords: Wood dust; Inhalable fraction; Minimal sampling time; Limit of detection; Limit of quantification

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INTRODUCTION

According to European Union (EU) 'Strategic Framework on Health and Safety at Work 2014–2020,' the commission proposes to revise and to introduce exposure limit values for 13 chemical agents because of the fact that cancer is the first cause of work-related deaths in the EU and 53% of occupational deaths are attributed to cancer (European Commission 2014). Wood dust, especially oak- and beech-wood dust from hardwood species are classified as carcinogenic substances. An average 2% of workers from over 179 million in the EU25 Member States are exposed to inhalable wood dust, and that amounts to 3.6 million workers. Increased risk of worker exposure to inhalable wood dust refers to 16% and 25% number of workers exposed to mass concentrations up to 5 mg/m^3 and up to 2 mg/m^3, respectively (Kauppinen *et al*. 2006). Oak- and beech-wood dust confer the highest risk of developing intestinal-type sinonasal adenocarcinomas (ITAC). The strong relation of ITAC to exposure to wood dust makes it a professional disease in some countries for carpenters and furniture makers (Llorente *et al*. 2009). Ramroth *et al*. (2008) provided evidence that occupational exposure to wood dust is an independent additional risk factor for laryngeal cancer. Galea *et al*. (2009) in study of the long-term changes in inhalation exposure to wood dust in the UK found decreasing trends. In the Croatian wood industry, comprehensive research of worker exposure to dust of hardwood species has shown that exceeding of limit values for total dust (N = 141) was measured on 33% samples and for respirable particles (N = 137) was measured on 24% samples (Čavlović *et al.* 2009). Increased risk of worker exposure to inhalable dust (concentration above 2 mg/m^3) was measured in 35% cases (Čavlović 2018). Health effect research on sawmill workers in Croatia has shown that the most frequently reported respiratory symptoms were dry cough, phlegm, and rhinitis symptoms. Research of occupational risk in Croatia involving environmental checking showed the presence of hazardous constituents of wood dust at levels above known thresholds for respiratory health effects, specifically airway inflammation in two sawmills. Exhaled breath condensate acidity (EBC pH) was evaluated, and remarkable decrease was observed in workers in one sawmill (Ljubičić Čalušić *et al.* 2013). However, airborne endotoxin and mould levels were higher than thresholds related to inflammatory changes in the airways (100 EU/m^3 and 10000 CFU/m^3, respectively), with noticeable difference between sawmills regarding mould levels (Sabolić Pipinić *et al*. 2010).

European Directive 2017/2398 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work prescribe the limit values of 2 mg/m^3 (3 mg/m^3 until 17 January 2023), which refer to mass concentration measured or calculated in relation to a reference period of 8 h exposure of workers (European Commission 2017). According to guidance of monitoring strategies for toxic substances for monitoring period and duration in praxis, the sampling time can be less than the full shift (8 h reference period), but for continuous, well-controlled processes with minimal variability, only. In such circumstances, the monitoring period may cover at least 25% of the working shift and include periods of high exposure (HSE 2006). In another published experiment, 1.0 h was choosed as the shortest sampling time for PM_{10} and 1.5 h for PM_1 and $PM_{1.5}$ (Farina 2010). Lee *et al.* (2011) choose sampling times 1 h to 4 h, which were adjusted according to the judgment of the on-site hygienist to obtain optimal particle deposition.

Davies *et al.* (1999) in their determination of mass concentration of inhalable end thoracic fractions of airborne particles from spruce wood, fir wood, and pine wood dust, excluded from analysis those samples whose mass was below the mass limit of detection (LOD) 0.029 mg (using 37-mm sampler, Gesamtstaub-probenahmesystem GSP, and Personal Environmental Monitor PEM sampler) and 0.070 mg (using Seven Hole Sampler SHS sampler). However, Demers *et al.* (2000), in determination of inhalable fraction of wood dust using the SHS personal sampler, used the laboratory obtained limit of detection (LOD) 0.013 mg. Research of workers exposure to wood dust in the Norwegian sawmill industry registered an LOD of 0.023 mg for thoracic dust using thoracic cyclones type BGI GK2.69 and 0.011 mg for inhalable dust using conical inhalable sampler CIS (Straumfors *et al*. 2018). According to a job exposure matrix based on past expert assessments and using 37-mm cassette, there were assigned LOD of 0.1 mg per sample for measurements before 1994 and LOD of 0.05 mg per sample from 1994 onwards (Sauvé *et al*. 2019). Douwes *et al*. (2017) in measurements of field blanks resulting LOD of 0.01 mg/m^3 using inhalabe parsonal air sampler PAS-6. Some other authors used mass of samples obtained by the LOD/$\sqrt{2}$ method (LOD divided by the square root of 2) instead of sample masses that were below the LOD which refers to that group of samples (Hornung and Laurence 1990; Demers *et al.* 2000; Vocht *et al.* 2006; Straumfors *et al*. 2018).

Taverniers *et al*. (2004) reports that the detection or quantification is impossible below the determination limit, but at these lower levels, the uncertainty of the detection/quantification measurement is higher than the actual value itself. In this context, the LOD is defined as the point at which a measured value is larger than the uncertainty associated with it. According to Taverniers *et al*. (2004), the LOD is a concentration point, where only the qualitative identification is possible but not accurate and precise quantification. Croatian technical report adopted from CEN/TR 15230 (2005), define the minimum sampled quantity for analysis (limit of detection and limit of quantification) with minimal sampling time (t_{min}), in other words – with minimal sampling time to collect a detectable (t_{LOD}) or a quantifiable (t_{LOQ}) amount of the samples.

The aim of this study was to calculate the minimal sampling times (t_{LOD} and t_{LOQ}) and the mass LOD and limit of quantification (LOQ), based on hardwood dust mass concentration from various woodworking places. This analysis of measured cases intends to contribute to estimation of the duration of sample collection for better reliability of the measurement method for determining the mass concentrations of respirable, inhalable, and total dust of hardwood species.

EXPERIMENTAL

Materials

The samples of respirable (N_R = 86), inhalable (N_I = 119), and total (N_T = 97) wood dust were collected during processing green and dry hardwood species (oak- and beech-wood) and particleboards as hard wood material. All wood dust particles were collected several times from the air at different woodworking places: from three sawmills (S) near a timber band saw and circular saw, three floor production factories (F) near a four side planer and drum sander, and in two carpentries (C) near a circular saw (Table 1). Wood dust samples were collected for 1 h to 8 h.

Table 1. Particles Samples from Various Woodworking Processes

Working Place in Sawmill (S), Factory, (F) and Carpentry (C)	Fraction of Samples	Woodworking Process and Material
S1	R, T	Log band saw (LBS) - green oak wood (gOw)
S2	R, T	
S3	I	Log band saw (LBS) - green beech wood (gBw)
S3	R, T	Circular saw (CS) - green oak wood (gOw)
F1	R, I	Circular saw (CS) - dry beech wood (dBw)
F2	R, T	Four-side planer (4SP) - dry oak wood (dOw)
F3	T, I	
F1	R, I	Drum sander (DRS) - dry oak wood (dOw)
F3	T, I	
F3	I	Four-side planer (4SP) - dry beech wood (dBw)
C1	R, T	Circular saw (CS) - dry oak wood (dOw)
C2	R, T, I	Circular saw (CS) - particleboard (PB)

R: Respirable fraction; T: Total dust; and I: Inhalable fraction

Methods

Determination of wood dust mass concentration

Determination of the mass concentrations of respirable, inhalable, and total wood dust from ambient air was performed using personal sampling pumps and three types of filter holders: Higgins-Dewell respirable dust cyclone manufactured by Casella (Bedford, UK), inhalable dust IOM sampler manufactured by SKC (Dorset, UK), and total dust 25-mm open-faced filter holder by Casella (Fig. 1).

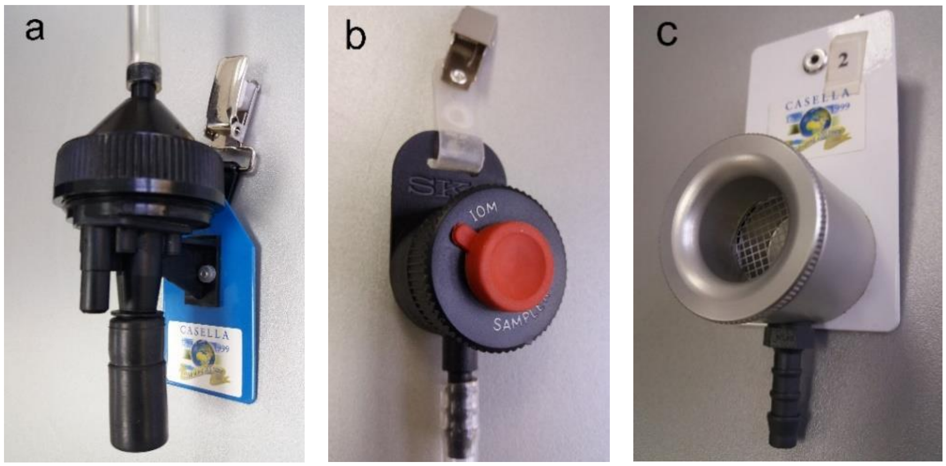

Fig. 1. Filter holders: a: respirable dust cyclone; b: inhalable dust IOM sampler; and c: total dust open-faced filter holder

Recommendations for wood dust sampling include the convention for measuring airborne particles as specified in CEN 481 (1993). Ten Casella Apex personal sampling pumps per day were used, set at the suction flow rate of 2 L/min in determining the mass concentration using inhalable dust IOM sampler and total dust open-faced sampler, or set at 2.2 L/min using respirable dust cyclone sampler. The measuring equipment, including a personal sampling pump and filter holder, are worn by the worker over the work suit during working operations (Fig. 2).

Fig. 2. Personal dust sampling near timber saw: a: total dust sampling in Sawmill 1; b: respirable dust sampling in Sawmill 3

Whatman 25-mm quartz filters (QM-A) were conditioned in the desiccator at 20 ± 1 °C and 50 ± 5% relative humidity for 24 h before weighing and before and after the sampling. Each filter was electrostatically discharged prior to weighing using a Mettler Toledo U-electrode. The weighing was performed using a micro-scale Mettler-Toledo MX-5 (Mettler-Toledo International Inc. Full Manufacturer Name, Greifensee, Switzerland) with 10^{-6} g scale sensitivity. Whatman 25-mm quartz filters were used for all measurements. The mass concentration of dust was determined using the gravimetric method according to the standard ZH 1/120.41 (1989).

Calculation of limit of detection, limit of quantification, and the minimal sampling time

Determination of mass concentrations of airborne particles requires repeating the collection of samples several times. When any systematic error is excluded during sampling, the mass of samples and standard deviation can be determined. In accordance with CEN/TR 15230 (2005), if the analytical LOD is conventionally considered to be three times the value of standard deviation of the samples mass (s_m, mg), then the minimal sampling time to collect a detectable amount of the substances (t_{LOD}) can be calculated according to Eq. 1,

$$t_{LOD}\ (h) = (3000 / 60) \times (s_m / m_c \times Q) \tag{1}$$

where Q is the air flow of the sampler (L/min) and m_c is the mass concentration of wood dust (mg/m^3).

Further, if the analytical LOQ is conventionally considered to be ten times the value of standard deviation of samples mass (s_m), the minimal sampling time to collect a quantifiable amount of the substance (t_{LOQ}) was calculated according to Eq. 2:

$$t_{LOQ}\ (h) = (10000 / 60) \times (s_m / m_c \times Q) \tag{2}$$

Because it was difficult to use a blank due to the small masses of the samples, the LOD and LOQ were obtained from the standard deviation (s_m) of the lowest masses (m_{min}) from a few samples of the group collected from the same woodworking place. The LOD was calculated as three times, and the LOQ as ten times, the values of those standard deviation as per CEN/TR 15230 (2005).

Statistical analysis

Regression equations were obtained from relation between the mass of all samples in the group and the minimal detection sampling time calculated from standard deviation of the samples mass and the mass concentrations of all samples in the group. Regression analysis, descriptive statistics, and Pearson's correlation analysis were made using Excel 2016 (Microsoft Corp., Redmond, WA, USA).

RESULTS AND DISCUSSION

The arithmetic average values of sample mass and mass concentration from various woodworking places are shown in Tables 2, 4, and 6, for respirable, total, and inhalable wood particles, respectively. The geometric mean as a better indicator of dust emission, was chosen to show the average value of the mass concentration of wood dust for all groups of samples as well.

During the processing of dry oak wood and beech wood in factory 3 and carpentry 2, the mass concentrations of the inhalable fraction for 48 samples of a total 119 inhalable samples (40%) exceeded the limit value of 2 mg/m^3, as the prescribed exposure limit of increased risk (Table 6).

The arithmetic means of minimal mass of samples in the group and calculated data of the mass limits and minimal sampling times for all group of samples, are presented in Tables 3, 5, and 7 for respirable, total, and inhalable wood particles, respectively. The minimal sampling time and the minimal quantification time (t_{LOD} and t_{LOQ}) were calculated according to Eqs. 1 and 2 from values of mass concentration and the air flow from which the samples of minimal mass were determined. The regression equations of the minimal detection sampling time *y* (h) as a function of the mass samples *x* (mg) are given in the Tables 2, 4, and 6.

Table 2. Mass of Samples (*m*), Mass Concentration (m_c) and Real Sampling Time (*t*) for the Group of Samples (*N*) of Respirable Wood Dust

Working Places	N	m [a] (mg)	m_c [a]	m_c [b]	t (h)	Regression Equation $t_{LOD} = am + b$
			(mg/m^3)			
S1-LBS-gOw	12	0.233 ± 0.116	0.380 ± 0.371	0.297	6.5	y = -38.159x + 25.267; R^2 = 0.36
S2-LBS-gOw	12	0.1303 ± 0.0447	0.1545 ± 0.0402	0.149	7	y = -54.156x + 14.773; R^2 = 0.91
S3-CS-gOW	13	0.3868 ± 0.1203	0.4805 ± 0.1732	0.446	7	y = -23.219x + 16.4; R^2 = 0.54
F1-CS-dBW	9	0.149 ± 0.061	0.158 ± 0.059	0.151	8	y = -39.811x + 16.031; R^2 = 0.92
F1-DRS-dOw	13	0.091 ± 0.024	0.099 ± 0.023	0.096	7.5	y = -63.138x + 12.147; R^2 = 0.90
F2-4SP-dOw	8	0.1368 ± 0.0196	0.1857 ± 0.0762	0.186	6.5	y = -45.265x + 9.05; R^2 = 0.85
C1-CS-dOw	11	0.3441 ± 0.1702	0.5977 ± 0.2684	0.539	5	y = -21.682x + 16.407; R^2 = 0.48
C2-CS-PB	8	1.024 ± 0.164	2.924 ± 0.783	2.842	3	y = -1.5918x + 3.108; R^2 = 0.60

a: Arithmetic means and standard deviations; and b: geometric means

Table 3. LOD, LOQ, and Minimal Sampling Times (t_{LOD} and t_{LOQ}) Based on the Minimal Mass of Samples in the Group (m_{min}) of Respirable Wood Dust

Working Places	n	m_{min} [a]	s_m	LOD	LOQ	t_{LOD}	t_{LOQ}
		(mg)				(h)	
S1-LBS-gOw	4	0.1590	0.008	0.023	0.076	0.95	3.18
S2-LBS-gOw	2	0.0495	0.008	0.023	0.078	2.19	7.31
S3-CS-gOw	2	0.1860	0.017	0.051	0.170	2.19	5.75
F1-CS-dBw	3	0.1110	0.007	0.021	0.070	1.44	4.81
F1-DRS-dOw	3	0.0650	0.005	0.140	0.045	1.64	5.45
F2-4SP-dOw	2	0.1105	0.008	0.023	0.078	1.54	5.15
C1-CS-dOw	4	0.1702	0.028	0.084	0.279	2.08	6.95
C2-CS-PB	3	0.9000	0.131	0.393	1.308	1.38	4.72
Average [b]:		**0.1216**	**0.012**	**0.052**	**0.114**	**1.72**	**5.51**

a: Arithmetic means; b: does not include data for Carpentry 2 (C2)

Wood dust collections in the tested cases would not take less than 1.72 h to 1.46 h on average for reliable detection or 5.51 h to 4.88 h for reliable quantification of respirable and total dust samples, respectively (Tables 3 and 5). The collection of inhalable samples in these cases would not take less than 1.12 h on average for reliable detection and 3.75 h for quantification (Table 7). A high mass concentration of particle types was measured in carpentry 2, so the LOD and LOQ values were higher than the other samples (Tables 3, 5, and 7). The arithmetic mean of the data in Tables 3, 5, and 7 does not include the data for carpentry 2 due to the noticeably high value and the assumption that significantly much more fine particles are generated during sawing of particleboards than in solid wood processing and are therefore not comparable. Data of Carpentry 2 are not included in correlation analysis (Table 8) as well.

Table 4. Mass of Samples (m), Mass Concentration (m_c) and Real Sampling Time (t) for the Group of Samples (N) of Total Wood Dust

Working Places	N	m^a	m_c [a]	m_c [b]	t	Regression Equation $t_{LOD} = am + b$
		(mg)	(mg/m^3)		(h)	
S1-LBS-gOw	14	1.223 ± 0.765	1.701 ± 1.106	1.406	6.5	y = -9.314x + 27.683; R^2 = 0.62
S2-LBS-gOw	12	0.617 ± 0.202	0.7424 ± 0.1877	0.721	7	y = -8.713x + 12.587; R^2 = 0.93
S3-CS-gOw	13	1.1286 ± 0.4209	1.151 ± 0.2561	1.130	7	y = -6.858x + 16.546; R^2 = 0.62
F2-4SP-dOw	8	0.747 ± 0.2546	1.1286 ± 0.4414	1.043	6	y = -3.597x + 7.461; R^2 = 0.48
F3-4SP-dOw	15	2.9385 ± 1.9465	3.1751 ± 2.0878	2.708	8	y = -4.179x + 32.662; R^2 = 0.73
F3-DRS-dOw	16	3.4288 ± 1.3409	3.6887 ± 1.4270	3.463	8	y = -2.360x + 18.334; R^2 = 0.90
C1-CS-dOw	11	2.3515 ± 1.2987	4.228 ± 2.6143	3.561	5	y = -3.963x + 20.180; R^2 = 0.55
C2-CS-PB	8	8.144 ± 1.087	23.019 ± 4.375	22.687	3	y = -0.0883x + 1.933; R^2 = 0.22

a: Arithmetic means and standard deviations; and b: geometric means;

Table 5. LOD, LOQ, and Minimal Sampling Times (t_{LOD} and t_{LOQ}) Based on the Minimal Mass of Samples in the Group (m_{min}) of Total Wood Dust

Working Places	n	m_{min} [a]	s_m	LOD	LOQ	t_{LOD}	t_{LOQ}
		(mg)				(h)	
S1-LBS-gOw	4	0.5733	0.046	0.138	0.460	1.67	5.56
S2-LBS-gOw	2	0.2765	0.039	0.117	0.389	1.95	6.51
S3-CS-gOw	2	0.6140	0.033	0.098	0.325	1.16	3.88
F2-4SP-dOw	2	0.3635	0.037	0.112	0.375	1.65	5.51
F3-4SP-dOw	2	1.2675	0.118	0.354	1.181	2.25	7.5
F3-DRS-dOw	3	2.1267	0.041	0.123	0.410	0.45	1.49
C1-CS-dOw	3	0.9427	0.076	0.227	0.755	1.11	3.70
C2-CS-PB	3	7.2403	0.618	1.853	6.176	0.72	2.39
Average [b]**:**		**0.8806**	**0.056**	**0.1670**	**0.556**	**1.46**	**4.88**

a: Arithmetic means; and b: does not include data for Carpentry 2 (C2)

Only in Carpentry 2, the samples of inhalable fraction whose mass is lower than LOD and LOQ, namely one sample (1%) of mass less than LOD and nine samples (8%) of mass less than LOQ were collected. In both Carpentries and Sawmill 2, 14 total samples (16%) of the respirable fraction of mass less than LOQ were collected. Three samples (3%) of total dust with a mass less than LOQ were collected in Sawmill 2 and Factory 2.

Pearson's correlation test results for all group of samples show that the real sampling time displayed a weak correlation with the minimal determination sampling time (k = 0.12) and the minimal quantification sampling time (k = 0.11).

Table 6. Mass of Samples (m), Mass Concentration (m_c), and Real Sampling Time (t) for the Group of Samples (N) of Inhalable Wood Dust

Working Places	N	m [a]	m_c [a]	m_c [b]	t (h)	Regression Equation $t_{LOD} = am + b$
		(mg)	(mg/m^3)			
S3-LBS-gBw	13	0.147 ± 0.0505	0.8664 ± 0.3442	0.798	1.5	y = -14.649x + 4.224; R^2 = 0.50
F1-CS-dBw	19	0.591 ± 0.244	0.626 ± 0.248	0.585	8	y = -14.021x + 19.349; R^2 = 0.90
F1-DRS-dOw	23	0.467 ± 0.268	0.549 ± 0.334	0.479	7	y = -20.480x + 25.060; R^2 = 0.77
F3-4SP-dOw	14	2.617 ± 1.8304	2.8102 ± 1.9723	2.475	8	y = -3.068x + 27.873; R^2 = 0.67
F3-DRS-dOw	15	4.5534 ± 3.0668	4.8283 ± 3.2394	4.255	8	y = -1.918x + 28.262; R^2 = 0.70
F3-4SP-dOw	15	0.2533 ± 0.2959	1.9275 ± 2.2388	0.795	1	y = -58.800x + 36.558; R^2 = 0.42
F3-4SP-dBw	10	0.345 ± 0.1718	3.6927 ± 1.5568	3.297	1	y = -4.286x + 3.006; R^2 = 0.49
C2-CS-PB	10	1.0727 ± 0.3864	12.38 ± 5.7770	11.080	1	y = -0.772x + 1.741; R^2 = 0.77

a: Arithmetic means and standard deviations; and b: geometric means;

Table 7. LOD, LOQ, and Minimal Sampling Times (t_{LOD} and t_{LOQ}) Based on the Minimal Mass of Samples in the Group (m_{min}) of Inhalable Wood Dust

Working Places	n	m_{min} [a]	s_m	LOD	LOQ	t_{LOD}	t_{LOQ}
		(mg)				(h)	
S3-LBS-gBw	2	0.0775	0.030	0.091	0.304	2.14	7.15
F1-CS-dBw	4	0.3620	0.025	0.074	0.25	1.60	5.34
F1-DRS-dOw	2	0.2680	0.018	0.054	0.18	1.69	5.62
F3-4SP-dOw	3	1.4857	0.039	0.116	0.386	0.62	2.06
F3-DRS-dOw	2	2.2915	0.049	0.146	0.488	0.49	1.65
F3-4SP-dOw	3	0.0097	0.003	0.010	0.032	0.74	2.47
F3-4SP-dBw	2	0.1405	0.030	0.091	0.304	0.59	1.98
C2-CS-PB	4	0.7510	0.215	0.645	2.151	0.65	2.17
Average [b]:		**0.6621**	**0.0278**	**0.083**	**0.278**	**1.12**	**3.75**

a: Arithmetic means; b: does not include data for Carpentry 2

A comparison of the mean values of the m_{min} and the sampling times t_{LOD} and t_{LOQ} for the group of samples of total and inhalable dust, as well as all types of fractions, exhibited a negative moderate correlation. The range of coefficient *k* was from -0.58 to -0.51 (Table 8.). This result suggested that a stronger influence of mass concentration on the collection of reliable samples of higher values of the m_{min} in a shorter time, compared to the second case of dustiness. Between the mean values of mass concentration for all groups of samples and minimal sampling times a negative moderate correlation was found for total dust and all types of fractions, with the range of coefficient *k* from -0.62 to -0.43, and a strong negative correlation was found for inhalable samples (k = -0.86) as well. From this data, it is apparent that collection of samples may be carried out over a shorter period and still be reliable in case of high concentrations of particles in the ambient air.

Table 8. Comparison of Minimal Mass Samples and Mass Concentration with the Minimal Sampling Times

Type of Aerosol	Pearson Correlation Coefficient, *k*			
	m_{min} - t_{LOD}	m_{min} - t_{LOQ}	m_c - t_{LOD}	m_c - t_{LOQ}
Respirable	- 0.04	-0.27	0.26	0.11
Total	- 0.58	- 0.54	- 0.49	- 0.43
Inhalable	- 0.54	- 0.53	- 0.86	- 0.86
All samples	- 0.52	- 0.51	- 0.62	- 0.62

Testing has shown that the reliability of the measurement is influenced more by the dustiness of the workspace than the real sampling time. Better reliability can be achieved using longer sampling times, especially with lower mass concentration of smaller particles. Additionally, it was observed in practice that great dissipation of mass samples and mass concentration values could happen by increasing of the sampling time with possibilities to dustiness oscillations that occurred during 8 h working shift at the same working place. Davis *et al*. (1999) determined total softwood dust exposure of workers in a lumber mill and obtained 25% samples below LOD. Similarly, Rosenberg *et al*. (2002) reported 4.5% samples mass concentration of inhalable dust below LOQ in sawmills. Teschke *et al*. (1999) determined inhalable dust exposure of workers in Canadian lumber mills and obtained all samples mass above LOD. In the Danish cross-sectional studies 6% measurements were below LOD for the inhalable wood dust mass concentration (Schlünssen *et al*. 2008). In quantitative estimates of total wood dust exposure in Canada, 43% of all samples were below LOD (Sauvé *et al*. 2019). Some other inhalable dust concentration measurements of field blanks resulting in 0.3% sample below LOD (Douwes *et al*. 2017).

Many authors have compared the results of reliability analysis of measurement methods using various personal samplers and filter holders (Davis *et al*. 1999; Teschke *et al*. 1999; Demers *et al*. 2000; Paik and Vincent 2002; Vocht *et al*. 2006; Farina 2010; Straumfors *et al*. 2018) or reported specific differences from several countries (Vocht *et al*. 2006). Farina (2010) obtained the minimal sampling time longer than 8-h working shift, which ranged from 8.69 h to 60.95 h (needed to collect 0.1 mg of dust that is the NIOSH limit of detection for PM_{10}, $PM_{2.5}$, and PM_1). Demers *et al*. (2000) in the study of exposure in Canadian lumber mills reported the LOD for softwood inhalable wood dust of 0.013 mg (based on the 3SDs lab blanks). Paik and Vincent (2002) have shown in general, that sample masses of inhalable particles equal to or higher than 0.19 mg and 0.65 mg can be confidently detected (LOD) and quantified (LOQ), respectively. However, for collection where the mass concentration is 1 mg/m^3 and less, it should be taken into account that these estimates would fall somewhere near or between their LOD and LOQ. Rosenberg *et al*.

(2002) presented the mass concentration of 0.1 mg/m^3 (for a 1,000-L air sample) as LOQ in determination of Finnish sawmills workers' exposure to pine and spruce wood inhalable dust.

CONCLUSIONS

1. This analysis provided a practical application involving realistic wood working conditions with variation of processing, wood material, filter holders, fractions of airborne particles, and range of mass concentration. Given the dust level assumption at woodworking places, this analysis is useful for the sampling time assessment when planning the mass concentration determination.
2. For minimizing measuring errors, these results are applicable for adjustment of sampling procedure to specific type and same working conditions. Thus, it should be emphasized the importance of careful handling of the filters with less possible errors in each stage of determination procedure that has an impact on the variability of the mass of samples.
3. These results contribute to a reliable estimate of the duration of sample collection for better reliability of the measurement method for determining the mass concentration of respirable, inhalable, and total dust of hardwood species.

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