Effects of Cutting Parameters on the Sound Level and Surface Quality of Sawn Wood

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This study investigated the effect of cutting conditions effects on sound level and surface quality in softwood and hardwood. The sound emission level caused by cutting process (band saw) as well as the surface roughness and topography of the wood samples were evaluated. A direct relationship was found between sound emission level and density, moisture content, feeding rate, and dimensions of the samples. Straight cutting of the samples caused less sound emission than cutting in a curved direction. The protective effect of the earmuffs was very significant, reducing the sound emission level from 88 dB to 38 dB. The results showed that with increasing the density and dimensions of the samples, the surface roughness decreased, while with increasing the moisture content and feeding rate, changing the cutting direction from straight to curved, the surface roughness of the samples increased.

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INTRODUCTION

Wood is one of the most stable, diverse, durable, environmentally friendly, and renewable raw materials in the world. The increasing tendency to use wood products shows the vast potential of wood for various purposes (Ali *et al.* 2019). Wooden composites are used as engineered components for use in construction and furniture production (Dineshkumar 2014). Exploitation of wood in carpentry and furniture factories requires the use of industrial machines such as saws.

People are exposed to all kinds of noises in living and working environments. In some work environments, exposure to sound is continuous (Sahin *et al.* 2017). Sound emission levels have direct and indirect effects (Parsons 2000; Ekerbicer and Saltik 2008; Ali 2011) on the health and productivity of the workforce. According to the World Health Organization (WHO), 250 million people lose their hearing each year (Owoyemi *et al.* 2016). The highest safe levels of sound emission in heavy equipment have been set by occupational health and environmental authorities (Sahin *et al.* 2017). Hence, the permissible sound level in industries according to the American Organization for Safety and Health (OSHA), the standard of European countries and the Eastern Bloc (BOSH, ISO), and the Iranian Technical and Occupational Health Committee is set at 90, 90, and 85 dB, respectively (ISO 3095 2014; Adams *et al.* 2016; Bies *et al.* 2017). In general, sound intensity of 66 to 150 dB causes a variety of mental, auditory, and physical disorders and other similar negative effects (Omoniyi and Fatoki 2018).

The intensity and frequency of sound in the wood industry depends on the species, material, length, thickness, and width of wood, as well as cutting depth, saw sharpness, saw feeding, and vibration of the cutting machine (Durcan and Burdurlu 2018). The band saw machine is one of the most widely used machines in wood industry factories; the operator is exposed on a daily basis (Guarnaccia *et al.* 2013). Factors such as wood species, sample dimensions, moisture content, cutting speed, sharpness, and thickness of the blade, the effectiveness of sawdust extraction, and blade cleaning systems affect blade vibrations (Tak *et al.* 2009; Owoyemi *et al.* 2016). With increasing density and length of wood samples, the level of sound emission in the cutting process increases (Vaishali *et al.* 2011). Robinson *et al*. (2015) showed that 44% of carpentry workers have hearing loss, and their hearing level is 93.9 dB.

In reports of 80 manufacturing sawmill and MDF (Medium-density fibreboard**)** production plants, all sawmills and 85% of MDF factories have a sound higher than the permissible level of human hearing (Javadi *et al.* 2018). In another study, the sound produced by band saws, panel saws, chainsaws, and side saws were reported at 99, 97, 108, and 96 decibels, respectively (Vaishali *et al.* 2011). Examination of the sound caused by tools such as band saws, circular saw machines, hammers, and nails in sawmills showed that these production facilities need to provide personal safety equipment (Guarnaccia *et al.* 2013).

Previous studies on sound emission in carpentry workshops have shown that with increasing distance of the operator from the source of the sound, the sound level decreases. People who are less than 10 meters away from the source of the sound are exposed to the negative effects of working with machines for several hours (Omoniyi and Fatoki 2018). One of the factors influencing the quality of wood surface is the cutting process (Thoma *et al.* 2015).

Several studies on the impact of wood species and cutting speed (Škaljić *et al.* 2009), machining parameters (Mitchell and Lemaster 2002) such as cutting angle, feeding speed, and blade type (Kilic *et al.* 2006; Malkoçoğlu 2007; Aguilera and Zamora 2009; Aguilera and Muñoz 2011; Azemović *et al.* 2014; Kminiak and Gaff 2015; Thoma *et al.* 2015; Vančo *et al*. 2017; Qing *et al*. 2018; Pinkowski *et al*. 2018) on the surface roughness of machined wood have been conducted (Akbulut and Koç 2006; Aguilera 2011). According to these studies, low roughness of wood is possible by choosing the correct angle parameters such as cutting angle, blade attack angle, and free angle (Škaljić *et al.* 2009). Pinkowski *et al*. (2018) showed that during milling of wood, the lowest surface roughness is observed at a cutting angle of 55° to 40° degrees. With increasing feeding speed, wood surface roughness increases, but with increasing wood density, the surface roughness decreases (Pinkowski *et al*. 2018). Various studies have confirmed the effect of anatomical characteristics such as the type and direction of fibers on the surface quality of machined wood (Goli 2003, 2004; Goli *et al.* 2004, 2005). Also, the use of hearing protection (HPDS) including earplugs and earmuffs have a significant effect on controlling low-frequency sound fluctuations (Nélisse *et al.* 2012).

This study investigated the effect of different variables on surface quality and sound emission due to cutting hardwood and softwood species in furniture workshops. The effect of using personal safety equipment in reducing these noise injuries was evaluated. Also in this research, an attempt was made to evaluate the amount of sound emission and roughness changes in the cutting process of Iranian native wood.

EXPERIMENTAL

Materials

Wood samples of different species of softwood (fir, cypress, and yew) and hardwood (poplar, beech, and oak) with dimensions of 100 × 100 × 52 mm^3 (L × R × T) were used (Fig. 1).

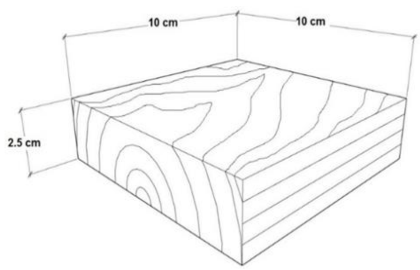

Fig. 1. A schematic view of the wood sample

Based on the anatomical and biological changes of wood and different growth conditions of trees, the age of the trees was different. The average age of the trees was 15 to 25 years with a diameter of 100 to 200 mm. All trees except fir species were prepared from native species of Iran. Also, the initial length of cut logs of hardwood trees was 280 cm, and the sampling site was considered at a height of 150 cm above the ground. The wood samples with moisture content above fiber saturation point (FSP) were cut to evaluate the sound emission at green moisture content. Other green samples were air dried and then kept in a conditioning room (65% relative humidity and 20 °C) for 1 month to reach 12% equilibrium moisture content (EMC). The moisture content was calculated using Eq. 1.

$$\text{Moisture content (\%)} = \frac{\text{Initial mass} - \text{Oven dry mass}}{\text{Oven dry mass}} \times 100\% \qquad (1)$$

The list of wood species used and their density is presented in Table 1. To measure the density, the division of mass and volume in moisture at 12% was used. This means that the water's mass is considered in the density.

Table 1. List of Wood Species and their Density

Wood Species		Density (g/cm^3)
Softwood	Fir (*Abies alba*)	0.40
	cypress (*Cupressus arizonica*)	0.47
	Yew (*Taxus baccata*)	0.59
Hardwoods	Poplar (*Populus nigra L.*)	0.4
	Beech (*Fagus orientalis*)	0.7
	Oak (*Quercus Castaneifolia*)	0.85

The treatments presented in Table 2 were used to evaluate the effective parameters in the cutting process. To examine the variable factors, some factors were considered fixed, which is shown in the status column (Table 1). Humidity parameters of 12%, dimensions of 100 by 100 mm^2, feeding rate of one (m/min), type of direct cutting and the use of Saw Fence were considered as fixed parameters. Three replications were used for each treatment.

Table 2. List of Studied Treatments

Parameter	Level	State	Treatment Code
Wood density	…….	Variable	WSG
Moisture (%)	12	Fixed	H12
	Green moisture content	Variable	H100
Dimension (mm^2)	100×100	Fixed	D 100×100
	200×200	Variable	D 200×200
Feed rate (m/min)	1	Fixed	FS1
	2	Variable	FS2
	3	Variable	FS3
Cutting type	Straight	Fixed	DC
	Curve	Variable	CC
Holder type	With saw fence	Fixed	WRF
	Without saw fence	Variable	WORF

Cutting Machine

A band saw made by Hossein Moghadamnejad Steel Factory (Karaj, Iran) with a diameter of 75 cm, a rotation speed of 1450 m/min, a three-phase motor power of 10 hp, and a blade with a thickness of 2 mm and a width of 4 cm was used. Cutting was done in a direction parallel to the wood grain and the measurement parameters were repeated in the cutting process (distance from the core) with the same pattern in all wood species.

Sound Emission and Safety Earphones

The Benetech GM1356 sound level meter was used to measure the sound emission level. The specifications of this device are shown in Table 3. To measure the sound, the location of the machine was adjusted to the distance of the operator's ear when working with the machine, so that the results are the same as the reality of the cutting operation process. Also, the average sound emission was used in this study.

To evaluate the effect of using personal protective equipment, earmuffs (Ultimate Industrial Company, model EP103, Karaj, Iran) were used (Fig. 2). The level of sound pressure was detected in the earmuffs by making a small hole and inserting a microphone (Rood Company, SmartLav Plus model, Karaj, Iran). To prevent sound penetration, the hole was blocked by polyurethane injection foam adhesive.

Fig. 2. Positioning of the operator in the evaluation of sound emission in the band saw

Table 3. Specifications of Sound Level Meter

Measuring range (dB)	30-130
Accuracy	1.5±
Frequency range	31.5 Hz-8.5 KHz
Resolution (dB)	0.1
Weight (gr)	244
Dimension (mm)	256×35×70

Roughness Test

A confocal laser scanning microscope (VK-9700, keyence, Göttingen, Germany) was used to evaluate the surface roughness and topography of the cut specimens. The CLSM with excitation wavelengths of 408 nm laser light source and Incorporating an Apo lens (N.A.: 0.95) of 50x or 150x magnification. After cutting the wood samples with a band saw, the surface cut in the radial section was evaluated CLSM microscopically. Due to the high accuracy of the device, the evaluation area was 1×5 mm in the radial direction.

Statistical Analysis

After collecting the results, the effect of treatments was investigated using analysis of variance. Also, Duncan's multiple range test was used to compare the mean of treatments and grouping between levels.

RESULTS AND DISCUSSION

Roughness Test

Table 4 shows the roughness of wood samples in different species. The results show that with increasing density, the surface roughness of the samples in hardwood and softwood species decreased. Pinkowski *et al.* (2018) also found that roughness decreased with increasing wood density. The highest and lowest surface roughness was observed in fir and yew as softwood species and in poplar and oak as hardwood species, respectively. Also, with increasing the moisture content of the samples from 12 to 100%, the surface roughness of the samples increased. The highest and lowest roughness was observed in fir and oak samples after reducing the moisture content to 12%, respectively. When the wood is higher than the fiber saturation point (FSP), the surface is deformed and fuzzy due to the high flexibility of the wood fibers after cutting. Also, these soft wood texture changes at high humidity ultimately increase the roughness of the wood surface after drying. With increasing dimensions in samples of hardwood species, surface roughness decreased, but no steady trend was observed in softwood. The results indicated that with increasing dimensions, the surface roughness increased in fir and cypress samples, while in yew samples the roughness decreased. In general, the changes in the amount of roughness due to the increase in the dimensions of the sample were variable, but not seriously significant. In curved cutting compared to straight cutting, surface roughness increased, and the highest and lowest surface roughness were observed in poplar and oak samples, respectively. The increase of roughness in curved cuts compared to straight cuts can be due to the change in cutting direction from parallel to the grain to perpendicular to the grain. Cutting the fibers in different directions caused the wood surface to become fuzzy. With increasing of the feed rate from 1 to 3 m/min, the surface roughness of the samples also increased and with increasing the feed rate in poplar with a density less than oak, more surface roughness was observed. This increase in roughness was due to the increase in the thickness of the chip and sawdust shavings. Pinkowski *et al.* (2018) and Kaplan *et al.* (2018) also achieved similar results and found that the roughness increased with increasing feed rate. In cutting samples without a saw fence, the surface roughness of the samples increased compared to cutting with a saw fence. In cutting without a saw fence, the highest and lowest surface roughness were observed in poplar and oak samples, respectively.

Table 4. Results of Roughness Test (µm)

Wood Species	Fixed factors	H100	D 200×200	CC	FS2	FS3	WORF
Fir	10.76^{a} (0.78)	12.1^{a} (0.24)	10.8^{a} (0.21)	10.9^{a} (0.4)	11.46^{a} (0.39)	12.86^{a} (0.8)	11.9^{a} (0.57)
Cypress	9.7^{a} (0.53)	11.3^{a} (0.37)	9.9^{a} (0.64)	9.93^{a} (0.61)	10.63^{a} (0.4)	11.93^{a} (0.34)	11.23^{a} (0.6)
Yew	7.36^{a} (0.29)	8.3^{a} (0.25)	7.2^{a} (0.43)	7.6^{a} (0.63)	8.6^{a} (0.35)	9.33^{a} (0.47)	9.16^{a} (0.17)
Poplar	11.37^{a} (0.45)	12.03^{a} (0.65)	11.26^{a} (0.37)	11.66^{a} (0.19)	11.93^{a} (0.45)	13.46^{a} (0.41)	12.36^{a} (0.42)
Beech	6.73^{a} (0.17)	7.63^{a} (0.25)	6.46^{b} (0.33)	6.83^{a} (0.04)	7.66^{ab} (0.17)	8.43^{ab} (0.57)	8.2^{a} (0.3)
Oak	5.1^{a} (0.24)	5.63^{b} (0.5)	4.8^{b} (0.16)	5.26^{b} (0.38)	6.43^{b} (0.26)	7.3^{b} (1.12)	6.86^{ab} (0.65)

The surface topography of wood species is presented in Fig. 3. According to the results, the surface roughness was decreased with increasing density of wood species. Figure 3 shows the amount of surface topography (CLSM) in different wood species due to cutting taking into account the fixed factors (Table 2). CLSM microscopic results show that poplar wood had a rougher surface than oak.

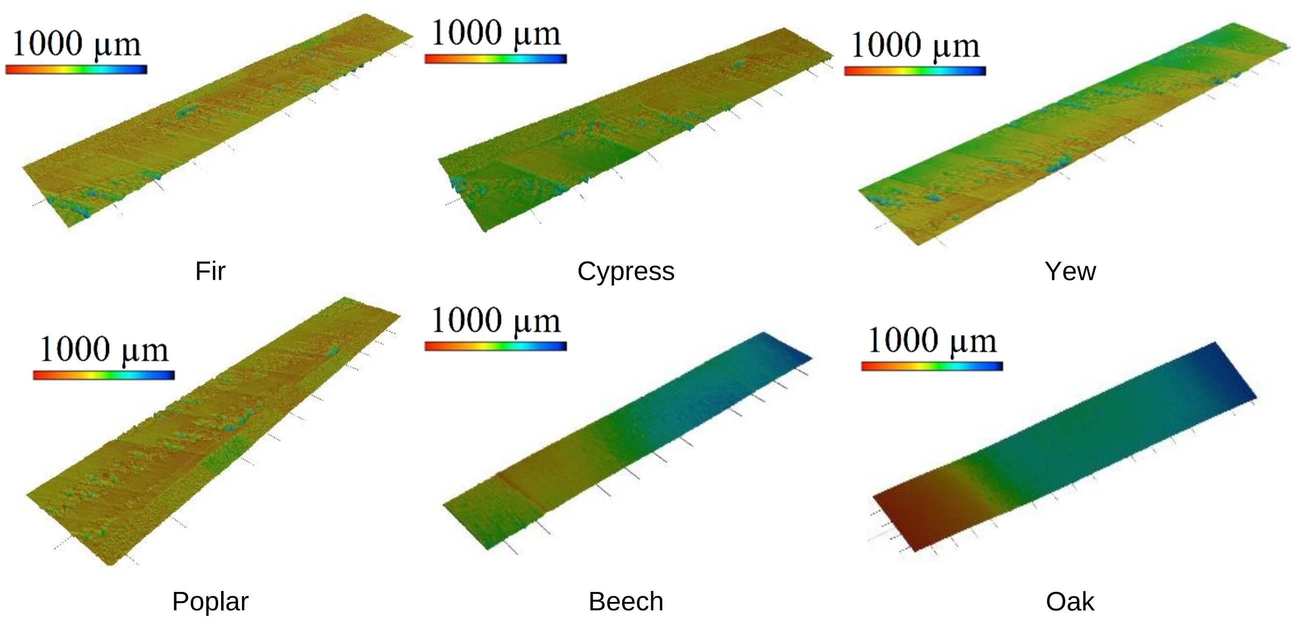

Fig. 3. Confocal microscopy images of the samples

Sound Level

Effect of Density

Figure 4 shows the results of the sound emission level of samples with different density. When only the machine was on and no cutting done, the sound emission level was 88 dB. Generally, the sound level was higher in hardwood species than in softwood. The lowest and highest sound levels were observed in poplar and oak samples, which were 4.9% and 23.1% higher, respectively, than the sound level when the machine was on and no cutting was taking place. The results also showed that the sound emission levels in cypress, yew, poplar and beech, increased by 8.29%, 11%, 5.3%, and 15.1%, respectively, compared to when the machine was on and no cutting was being done. Škaljić *et al*. (2009) found that with increasing the feeding rate of woodcutting from 6 m/min to 24 m/min, the roughness of the wood surface increased. According to the results of the present study, only oak samples were significantly different from other wood species. Also, the relationship between wood density and sound level was observed as $y = 2.725x + 85.614$.

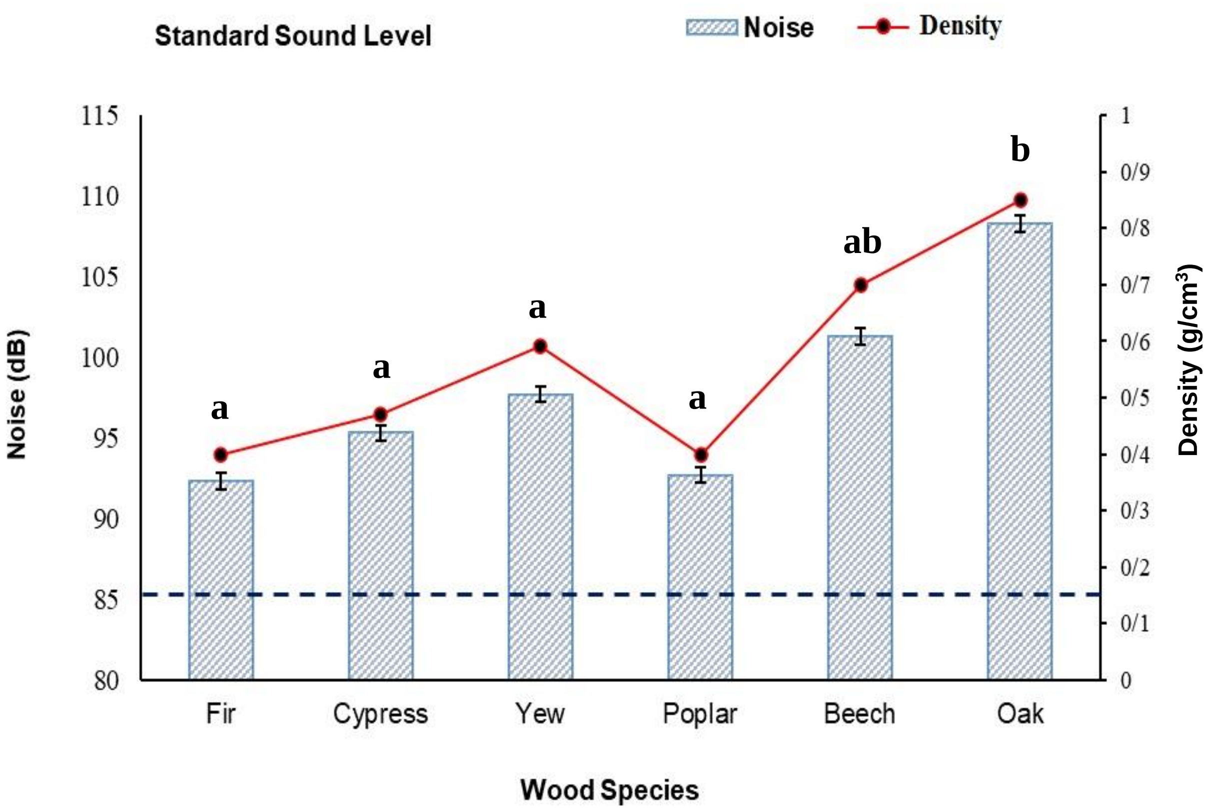

Fig. 4. Average sound level in the cutting process of different wood species

Effect of Moisture Content

Table 5 shows the results of the sound level test in samples with a moisture content of 12 and green (MC). The results showed that with increasing the moisture content from 12 to green (MC), the sound emission level decreased. The sound emission level was higher in hardwood species than in softwood species, and the lowest and highest sound levels were observed in poplar and oak samples, respectively. Tak *et al.* (2009) reported that wood cell walls at low moisture have a more brittle structure than higher moisture and sound level in woods with less moisture is higher than samples with more moisture. The sound emission levels due to cutting of wood samples at 100% moisture for fir, cypress, yew, poplar, beech and oak were estimated to be 2.6, 4.9, 6.8, 3.1, 3.7, and 11.4 higher, respectively, compared to when the machine is on and no cutting is performed. According to the results, the difference in sound level between softwood species at 12% moisture was not significant, while among hardwood species, only oak showed significant differences with other species. The difference in sound level may be caused by the density difference. In samples with green moisture content, no significant difference was observed between the sound level values in wood samples of all species.

Table 5. Average Sound Level in Samples with Different Moisture Content

Wood Species	H12	H100	Noise Decrease (dB)
Fir	92.3^a	90.3^a	2
Cypress	95.3^a	92.3^a	3
Yew	97.7^a	94^a	3.7
Poplar	92.7^a	90.7^a	2
Beech	101.3^a	95.7^a	5.6
Oak	108.3^b	98^a	10.3
Note: The different letters indicate a significant difference within columns			

Effect of Wood Dimensions

The results of sound test for samples with surface dimensions of 100×100 and 200×200 mm^2 are presented in Table 6. By increasing the dimensions of the samples from 100×100 to 200×200 mm^2, the sound level in all samples increased during cutting. Vaishali *et al.* (2011) stated that the sample dimension is one of the parameters affecting the sound level, so that increasing the length and width of the samples due to the increase and expansion of sound transmission from the cutting line to the surrounding environment, causes more noise. In the present study, among softwood and hardwood samples, the highest sound level during cutting was 110.3 dB, which was observed in oak species. The results indicated that in samples with dimensions of 100×100 mm^2, there was a significant difference between samples of oak species and others. However, in samples with dimensions of 200×200 mm^2, a significant difference was observed between beech and oak samples with others.

Table 6. Average Sound Level in Wood Samples with Different Dimensions

Wood Species	D 100×100	D 200×200	Noise Increase (dB)
Fir	92.3^a (0.5)	94^a (0.1)	2.3
Cypress	95.3^a (0.5)	97.3^a 0.5)	2
Yew	97.7^a (0.5)	99.3^a (0.5)	1.6
Poplar	92.7^a (0.5)	94.3^a (0.5)	1.6
Beech	101.3^a (0.5)	103.3^b (0.5)	2
Oak	108.3^b (0.5)	110.3^b (0.3)	2
Note: The different letters indicate a significant difference within columns; parentheses indicate standard deviation			

Effect of Cutting Type

The results of the sound level test for straight and curved cutting specimens are given in Fig. 5. In all samples, the sound level in the direction of curved cutting was higher than for direct cutting. The rate of increase in sound level due to curved cutting compared to direct cutting in poplar, cypress, yew, poplar, beech, and oak samples was 2.6, 3.6, 4.7, 3.9, and 3.7%, respectively. In straight and curved cutting modes, the sound level of oak showed a significant difference compared to other samples of softwood and hardwood. The difference in sound level may be caused by the density difference.

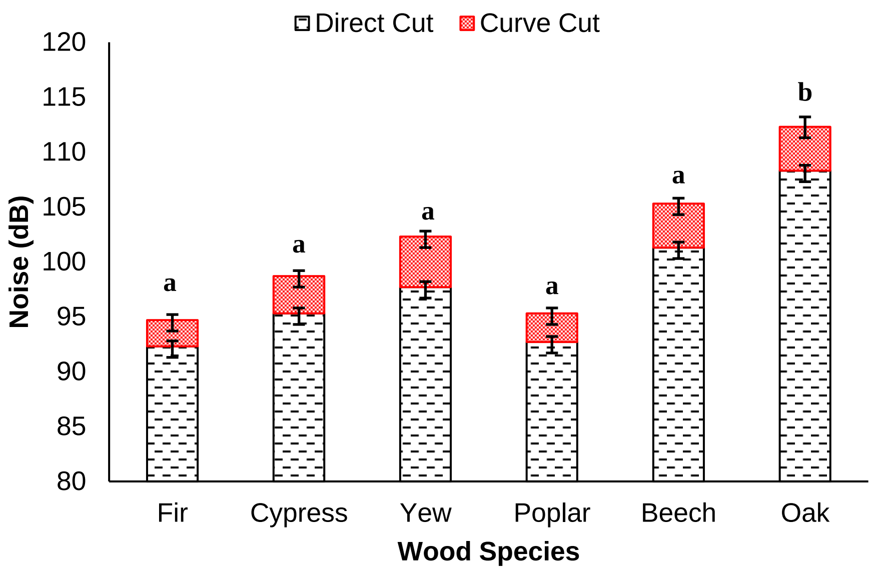

Fig. 5. Average sound level in straight and curved cut samples

Effect of Feed Rate

Figure 6 shows the results of sound level test for the cut samples with feed rates of 1 (FS1), 2 (FS2) and 3 (FS3) (m/min). According to the results, with increasing the feed rate from 1 (m/min) to 3 (m/min), the sound emission level increased in all samples of softwood and hardwood. By comparing the sound emission levels at all cutting levels (1, 2, and 3 m/min), the lowest and highest sound levels were observed in fir (92.3 dB) with a feeding rate of 1 m/min and oak (112.3 dB) with a feeding rate of 3 m/min, respectively. Also, the lowest and highest rate of increase in sound level compared to the load-free saw mode were obtained in fir (4.9%) with a feeding rate of 1 m/min and oak (29.5%) with a feeding rate of 3 m/min, respectively. Statistical analysis showed that oak had significant differences compared to other species in terms of feeding rate. Škaljić *et al*. (2009) found that with increasing the feeding rate of woodcutting from 6 m/min to 24 m/min, the roughness of the wood surface increased.

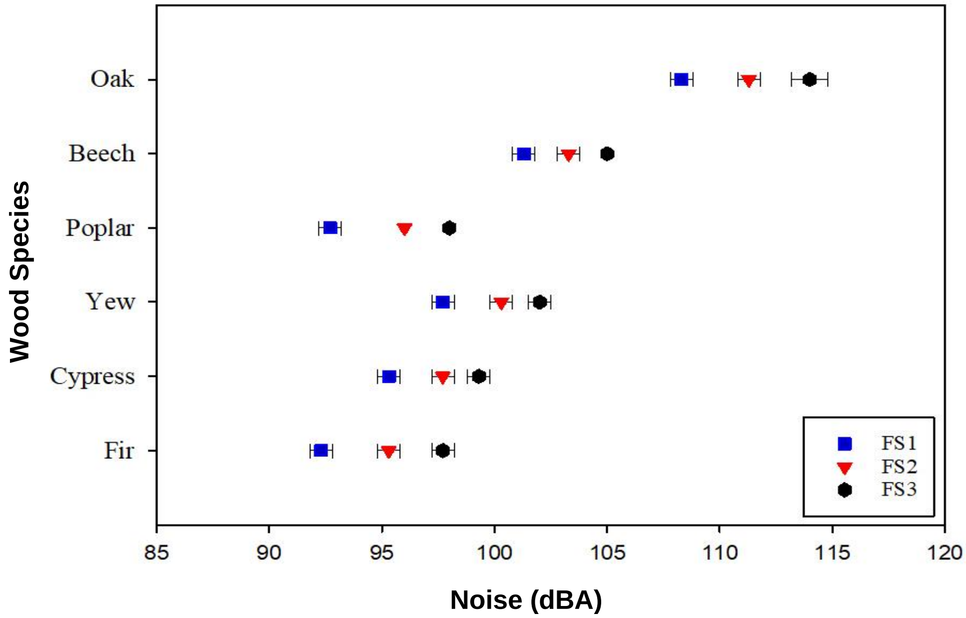

Fig. 6. Average sound level at different feed rates

Effect of Saw Fence

The results of sound level tests for wood samples during use and non-use of saw fence are shown in Table 7. The use of saw fence reduced the sound emission level during the cutting process. In both cutting modes (with saw fence/ without saw fence), the lowest and highest sound emission level were observed in fir and oak species, respectively. The results showed that there was no significant difference in the cutting of specimens using saw fence, while in cutting specimens without saw fence, a significant difference was observed between oak species and others. Which can be attributed to the higher density of oak wood species. Vaishali *et al.* (2011) reported that the use of a saw fence reduces the level of vibration and noise from the cutting process due to the connection of the wood specimens to the side wall. This ultimately makes the cutting process more accurate and quality, as well as less noise pollution. According to Vaishali *et al*. (2011), if the saw fence is not used in the cutting process, more noise pollution will occur due to increased vibrations.

Table 7. Average Sound Level of Cut Samples With/ Without Saw Fence

Wood Species	WRF	WORF
Fir	92.3[a] (0.5)	95.7[a] (0.5)
Cypress	95.3[a] (0.5)	98.7[a] (0.5)
Yew	97.7[a] (0.5)	102.3[a] (0.5)
Poplar	92.7[a] (0.5)	96[a] (0)
Beech	101.3[ab] (0.5)	105.3[ab] (0.5)
Oak	108.3[ab] (0.5)	113.7[b] (0.5)

Effect of Using Earmuffs

The results showed that the use of protective earphones in different test conditions reduced the sound emission level to 38 ± 2 dB. Nélisse *et al.* (2012) found that in different factories and workplaces of furniture production, there are significant fluctuations in sound emission. The use of hearing protection (HPDS) including earplugs and earmuffs had a significant effect on controlling low-frequency sound fluctuations. The amount of sound emission in different processes was evaluated by placing a microphone inside the earmuffs. However, due to the low changes in sound emission in the studied parameters, no significant change was observed in the sound propagation in the earmuffs. In other words, earmuffs reduce all these sound emission due to the layers of sound protection.

CONCLUSIONS

1. The type of wood (hardwood or softwood), moisture content, and dimensions of samples, as well as the feeding rate, use or non-use of saw fence, and type of wood cutting were the factors influencing the sound emission level during sawing.
2. Wood samples with higher density, dimensions, and moisture content showed higher levels of sound emission. With increasing density and volume of wood materials, the friction rate of the wood cutting process increased, which eventually caused the blade to heat up and make more noise.
3. The 100% moisture saturation of wood caused cell cavities to be filled with water, which reduced the cutting speed and led to sound reflection. On the other hand, increased vibrations due to higher feeding rate, and cutting in the direction perpendicular to the fibers without using a saw fence, increased the level of sound emission.
4. When using a saw fence, the vibration of the wood samples was reduced, and as a result, the sound level was reduced. In the present study, all values due to the performance of woodworking machines were higher than the standard noise emission level (85 dB). The use of earmuffs was very effective due to creating an acoustic barrier and reducing noise pollution up to 38 dB.
5. The use of personal safety equipment in workshops and factories of wood industries is essential. In addition, equipping tools in wood workshops with sound insulation such as acoustic fence, acoustic foam and special fences on the sidewalls are also essential solutions.
6. Based on the results, it can be suggested that in order to reduce the roughness of the wood surface and cause noise pollution in furniture factories, it is better to consider the following parameters: (1) use of dry wood; (2) slower feeding rate; (3) making joint and secondary cuts in smaller wood pieces; (4) cutting in the direction parallel to the fibers; and (5) using the saw fence in the cutting process.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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