Investigating operator vibration exposure time of 13 hp power tiller fuelled by diesel and biodiesel blends

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Abstract

Heidary B., Hassan-Beygi S.R., Ghobadian B., 2014. **Investigating operator vibration exposure time of 13 hp power tiller fuelled by diesel and biodiesel blends**. Res. Agr. Eng., *60*: 134–141.

One of the most useful agricultural machinery is power tiller; this kind of tractor is widely used in small fields. The operators of this kind of machinery are exposed to high level of vibration. Long time working with these machinery causes dynamic disorders, damaging different parts of the body, digestion disorders and vascular diseases. In this research, vibration acceleration of 13 hp power tiller was collected in 5 levels of engine speed and 6 kinds of consumed fuel blends investigating the power tiller vibration exposure time. The data were analysed by factorial tests with completely random design. The results showed that reciprocal effect of fuel and engine speed are prominent in 1% level. The working conditions of the power tiller operator fall into the highest class of risk according to ISO 5349-2 (2001) and in less than 4 years White Finger Syndrome may have induced in 10% of operators. Results of experiments revealed that the exposure time decreases with increase in engine speed especially in 1,800 and 2,200 rpm. The reason is the vibration intensification that happened in handle of power tiller in 1,800 rpm engine speed so it reduced the exposure time severely. The latency period for the appearance of vibration-induced White Finger Syndrom in biodiesel 10%, 15% and 20%, respectively, so using diesel fuel can be replaced by these three kinds of fuel in power tillers.

Keywords: white finger; vibration acceleration; highest class of risk; working conditions

The vibration that human is exposed to is produced in machines with internal combustion engine and from the moment of internal combustion engine invention and their subsequent improvement in manufacturing and technology, some problems existed such sound and vibration production, wide use of oil resource, danger of finishing the oil resources, and the combustion of these fuel increases the greenhouse gases, ozone layer destruction, environment pollution, various outbreak diseases and respiratory diseases in big cities. As these problems appear, many researches in the world have done experiments to find appropriate fuel. Between different kinds of fuels, renewable herbaceous fuels have a special place in fuel consumer countries. These fuels have an herbaceous or animal basis (Carratto et al. 2004; Ghobadian, Khatamifar 2006) and during combustion, less pollution is produced compared to fossil fuel (Dorado et al. 2004). Biodiesel is produced from herbaceous, animal and residual oils, and it seems appropriate because of nonexistence of uncomplimentary materials such sulfur, nitrogen, polycyclic aromatics and air pollution and also existence of similar traits with diesel fuel (Lee et al. 2004).

One of the most useful agricultural machinery is power tiller; this kind of tractor is widely used in small fields as power resource for doing the agricultural operations. Economic advantages and control abilities of power tillers in different conditions and roads cause an increase in using these tractors for transportation of agricultural products and human beings in fields and rural roads (Sam, Kathrivel 2006; Taghizadeh 2007; Dewangan, Tewari 2009). There are more than 120,000 power tillers in Iran (Hassan-Beygi, Ghobadian 2005; Hassan-Beygi et al. 2009). Agricultural machinery which is completely conducted with hand transmits much vibration to the human body. According to Okunribido et al. (2006), finding and determining the computed values of aggregate exposure in seven predefined occupational groups, it was suggested that tractor drivers are high-risk groups (had high values of two or more of the three exposure measures). The operators of this kind of machinery are exposed to high level sound and vibration and long time working with this machinery cause dynamic disorders, damaging different parts of body such: earache, spine and digestion disorders and vascular diseases (Salokhe et al. 1995; Tewari et al. 2004; Sam, Kathrivel 2006). Furthermore it causes a decrease in efficiency and work quality downfall (Tewari et al. 2004).

Regarding to fossil fuel problems, using renewable energies is a necessity. A change in kind of fuel causes changes in combustion process of internal combustion engine. The main portion of power tiller vibration is due to the diesel engine, so using the biodiesel fuel causes a change in vibration behavior in these kinds of tractors. Investigation of the resources showed some researches that were done on sound and vibration of power tillers using conventional fossil fuel (Hassan-Beygi, Ghobadian 2005; Taghizadeh et al. 2007; Sam, Kathrivel 2006, 2009; Dewangan, Tewari 2009) but vibration behavior of power tiller fuelled by biofuel and specially diesel and biodiesel blends has not been investigated till now. So in this research the exposure time of power tiller operator is investigated with different diesel and biodiesel blends in stationary mode. The results of this research can be used for choosing appropriate diesel and biodiesel blends from min. vibration production and max. exposure time point of view.

MATERIAL AND METHODS

Theoretical consideration. The basis of machine vibration is the use of root mean square (rms), it can be represented as:

$$a_{\mathrm{rms}} = \left[\frac{1}{T}\int_0^T a(t)^2\,dt\right]^{1/2} \tag{1}$$

where:

a_{rms} – acceleration root mean square (m/s^2)

t – acceleration domain (m/s^2)

T – acceleration period (s) (Mansfield 2005)

For vibration assessments, individual measurements made in orthogonal axes should be combined (Mansfield 2005). Vibration occurs in three translational axes and therefore the measurement should be performed in three axes – lateral, longitudinal and vertical. The coordinate system will then be defined as in ISO 5349-2 (2001). Z-axis, directed along the third metacarpus bone of the hand; X-axis, perpendicular to the palm surface area (both these axes are normal to the longitudinal axis of the grip); and Y-axis, parallel to the longitudinal axis of the grip.

Human response to vibration is dependent on the frequency of vibration. In the ISO 5349-2 (2001) recommendation, the rms frequency weighted vibration is the most important parameter used to describe the magnitude of vibration transmitted to the operators' hands.

Human perception to vibration is high at low frequency and the perception greatly decreases with frequency, so the weighting factor for vibration varies with frequency. The frequency-weighted vibration acceleration is calculated by ISO 5349-2 (2001) standard schedule (Griffin 1996; Goglia et al. 2006; Dewangan, Tewari 2009).

Weighted acceleration value a_{hw} was determined as below (ISO 5349-2 2001; Goglia et al. 2006; Dewangan, Tewari 2009):

$$a_{hw} = \sqrt{\sum_{j=1}^{n}(k_j a_{h,j})^2} \tag{2}$$

where:

k_j – weighting factor for jth frequency according to ISO 5349-2 (2001) standard factors (from 1 to 0.0125)

$a_{h,j}$ – rms measured in one third octave band (m/s^2)

n – number of frequencies used in one third octave band (from 6.3 to 1,250)

Table 1. Specifications of the power tiller under test

Engine	internal combustion system, indirect injection
No. of cylinders	single
Stroke cycle	4 stroke
Air intake system	naturally aspirated
Cooling system	water cooled
Rated engine speed	2,200 rpm
Power at rated speed	13 hp
Other specifications	type of clutch dry, multi-plates

The evaluation of vibration exposure time in accordance to ISO 5349-2 (2001) is based on three axes vibration combination so the vibration total value a_{hv} is described as total rms of three components value and shows the total vibration acceleration of three axes. a_{hv} was determined as below (ISO 5349-2 (2001); Goglia et al. 2006; Dewangan, Tewari 2009):

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \tag{3}$$

where:
a_{hv} – total rms acceleration (m/s^2)
a_{hwx} – total weighted vibration acceleration in X-axis (m/s^2)
a_{hwy} – total weighted vibration acceleration in Y-axis (m/s^2)
a_{hwz} – total weighted vibration acceleration in Z-axis (m/s^2) (Mansfield 2005)

Vibration exposure time depends on the magnitude and duration of operator's exposure to vibration, the assessment of vibration exposure is primarily based on daily exposure. The daily exposure depends on the magnitude and the daily duration of operator vibration exposure. For 8-hour daily work, exposure time is defined as below (ISO 5349-2 2001; Dewangan, Tewari 2009):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \tag{4}$$

where:
$A(8)$ – daily exposure time (h)
a_{hv} – total rms acceleration (m/s^2)
T_0 – 8 h reference time (h)
T – total vibration exposure time (h)

Also the vibration yearly exposure time can be defined as relation below:

$$D_y = 31.8(A(8))^{-1.06} \tag{5}$$

where:
D_y – yearly exposure time (year)

Equipment and procedure. In this research the vibration of 13 hp power tiller was measured in stationary mode on the asphalt surface in open area. The properties of power tiller are in Table 1. The instruments used in this study consisted in a power tiller (13 hp, Kubota, Torrance, USA), three accelerometers (CTC-AC 102-1A; CTC, Inc., Victor, USA), a tachometer (Lutron DT- 2268, Lutron, Taipei, Taiwan), a laptop computer and a few other devices. The detailed specifications of the instruments are given in Table 2.

The measurement of vibration acceleration was done in three directions (lateral, longitudinal and vertical) according to ISO 5349-2 (2001) standard (Fig. 1), simultaneously at the same time measuring of vibration was done by piezoelectric sensor (CTC-AC 102-1A) supplied by a source of power and electric circumstance (made by myself). The sensors were installed on a light metallic cube and the cube installed on a handle by a strong metallic grip (Fig. 2). External analogue voltage of sensors was changed to digital signal by an analogue to digital convertor (A/D) and the digital data were

Table 2. Specification of the instruments used in tests

Name of instrument	Model	Accuracy	Range
Accelerometer	CTC-AC 102-1A; CTC, Inc., Victor, USA	0.5 Hz	0.5–15,000 Hz
Tachometer	USALutron DT- 2268; Lutron, Taipei, Taiwan	1 rpm	1–20,000 rpm
Laptop computer	Sony VPC-F12-LGX; Sony, Tokio, Japan	–	–
SW recording vibration signals data	USB 4711A; Advantech America, Milpitas, USA	–	–
Analysis SW	Matlab Ver. 7; Math Works, Natick, USA	–	–

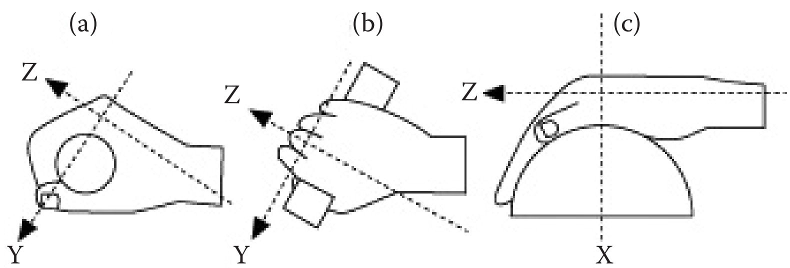

Fig. 1. Orientation of the axes for the vibration measurement on the power tiller (ISO 5349-2) (a) hand in side view, (b) hand in top viw, (c) hand in flat viw

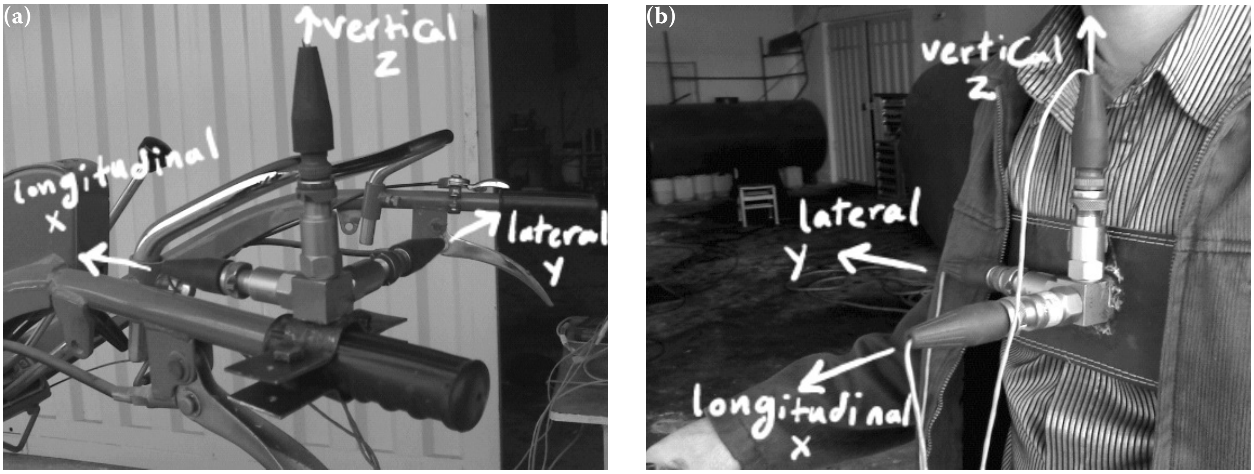

Fig. 2. Monitoring of accelerometers and orientation of measurement axes (a) handle (b) chest of operator

shown and saved in the laptop at the same time. The equipment that was used for this research is shown in Fig. 3.

In this research six blends of diesel and biodiesel fuel were used (D, B5, B10, B15, B20 and B100) and also tests were done by five levels of engine speed (1,400; 1,600; 1,800; 2,000 and 2,200 rpm). The vibration was measured in three axes.

Experiments were conducted in stationary experiments. The reason of investigating of vibration acceleration in stationary mode was its stability; this mode could be used for investigating and comparison with other modalities; furthermore it could be used as a basis of vibration assay.

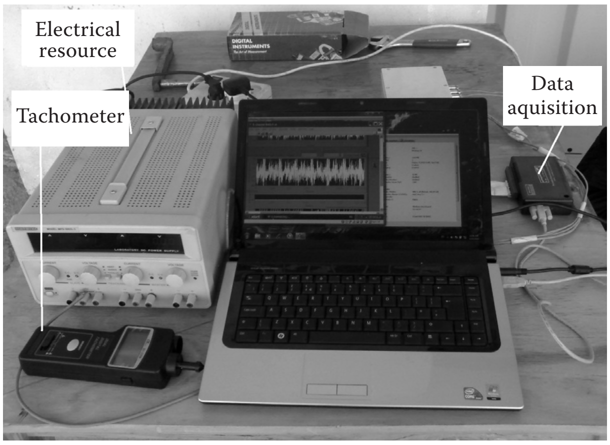

Fig. 3. Equipment used for the vibration measurement

Data collection and analysis. External data of A/D convertor were shown and saved in the laptop at the same time by Labview 2009 software. The signal of each accelerometer sensor was shown and saved in laptop separately. The software that was used for converting the time domain signals to frequency domain signals was Matlab 7 (Ver. 7, Math Works, Natick, USA) and data conversion was done by use of the fast Fourier transform (FFT). Comparison of the dependent parameters was complicated; one third octave band analysis was useful, so a digital one third octave filter suggested in ISO 5349-2 (2001) designed in Delphi software (Ver. 7, Embarcadero Technologies, San Francisco, USA) and narrow band signals changed to broadband (one third octave) signals by this filter. A sample of signal transforms from time domain to frequency domain and from frequency domain narrow band to frequency domain broadband is shown in Fig. 4.

The rms values of signals were calculated according to Eq. (1) in one third octave band, then the frequency weighted rms values of vibration intensity (a_{hwx}, a_{hwy} and a_{hwz}) were calculated by Eq. (2)

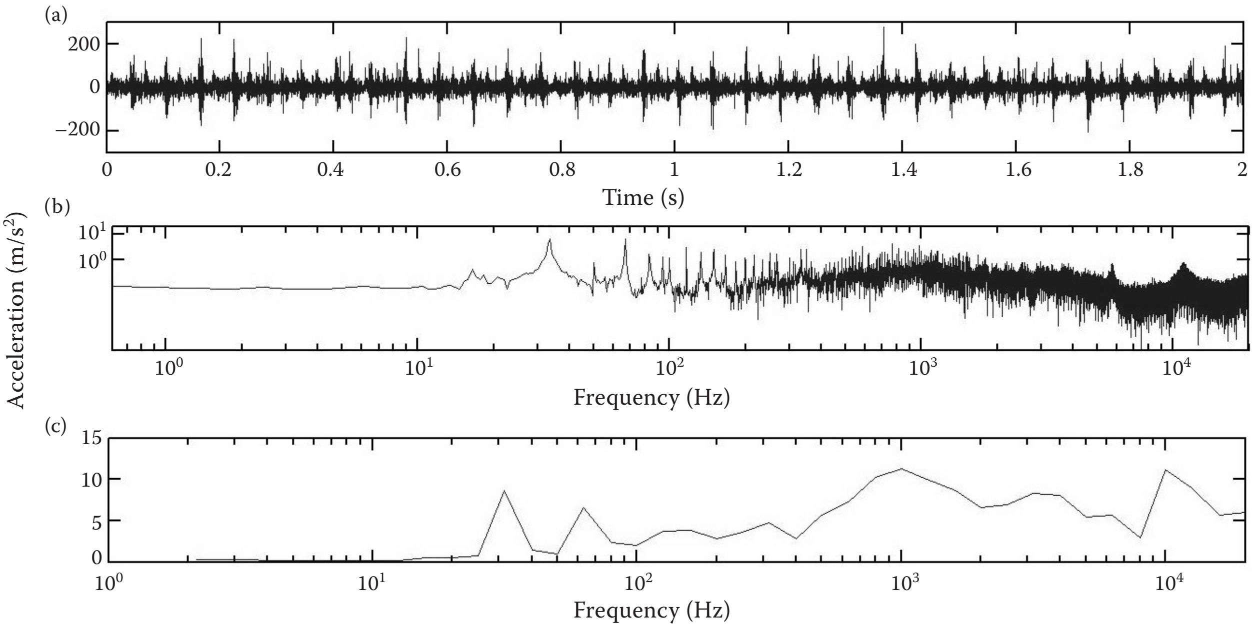

Fig. 4. Sample of signal transforms (a) time domain (b) frequency domain and (c) broadband

according to the weighted factors suggested in ISO 5349-2. The total weighted vibration acceleration (a_{hv}) was calculated by Eq. (3) and vibration exposure time was calculated for 6 kinds of fuel blends and 5 levels of engine speed by Eq. (5). The vibration exposure time was analyzed statistically by using factorial tests with completely random design in SAS (Ver. 9; SAS Institute, Cary, USA) and MS Excel (Ver. 2007; Microsoft office, Redmond, USA) software, for obtaining the effect of speed and fuel blends.

RESULTS AND DISCUSSION

Exposure time

This paper presents the results of exposure time quantities (years) in a stationary condition in 6 levels of engine speed and 6 kinds of diesel and biodiesel fuel blends.

Data were analyzed for vibration acceleration in rms (a_{hj}) at 1/3 octave band in the frequency range between 2.15 and 20,000 Hz for each test fuel mixture and each axis. For each axis the frequency-weighted rms acceleration (a_{hwx}, a_{hwy} and a_{hwz}) was calculated using the filter suggested by ISO 5349-2 (2001). An average of the three trials to test was calculated. Vibration total value (a_{hv}) was calculated for each test fuel mixture. Vibration exposure during operation of the hand tractor was calculated for each test fuel blend as in ISO 5349-2 (2001). Finally an optimum percentage of biodiesel and diesel mixture was represented.

In considering the effect of engine speed and fuel blends variants at exposure time, the parameter of engine speed and fuel blends and the reciprocal effect of engine speed and fuel blends are promi-

Table 3. Analysis of variance (mean square) of exposure time (years)

No.	Variant source	Degree of freedom	Mean square
1	repetition	2	0.00005^{ns}
2	engine speeds	4	8.22*
3	fuel blends	5	0.46*
4	engine speeds × fuel blends	20	0.22*
5	error	58	0.00003^{ns}

*means significant at the 1% level; ^{ns}not significant

Table 4. Vibration exposure time (years) on different fuel blends at various engine speeds

Engine speed (rpm)	Fuel blends					
	D	B5	B10	B15	B20	B100
1,400	3.10	3.16	3.82	3.78	3.54	3.53
1,600	3.08	3.67	3.51	3.25	3.21	3.22
1,800	1.28	1.22	2.19	2.02	1.75	1.77
2,000	3.23	2.28	2.88	3.40	3.24	3.22
2,200	2.27	2.45	2.97	3.07	2.90	2.85

nent in 1% level as is shown in Table 3. the variance analysis in SAS software is done and the results are shown in Table 4. Comparison of the mean squares is shown in Table 4 and Figs 5 and 6.

As it is observed in Table 4, working conditions of the power tiller operator fall into the highest class of risk according to ISO 5349-2 (2001) and in less than 4 years White Finger Syndrome may have induced in 10% of operators. The best fuel blend from the viewpoint of min. risk of inducing to White Finger Syndrome according to Table 4 and Fig. 5 are biodiesel 10% with 3.82 year in 1,400 rpm; biodiesel 15% with 3.78 in 1,400 rpm and biodiesel 5% with 3.67 year in 1,600 rpm of engine speed. Fig. 5 shows that between B10 and B100 vibration exposure time is more than diesel and B5 and the reason could be more perfect combustion of fuel in the engine.

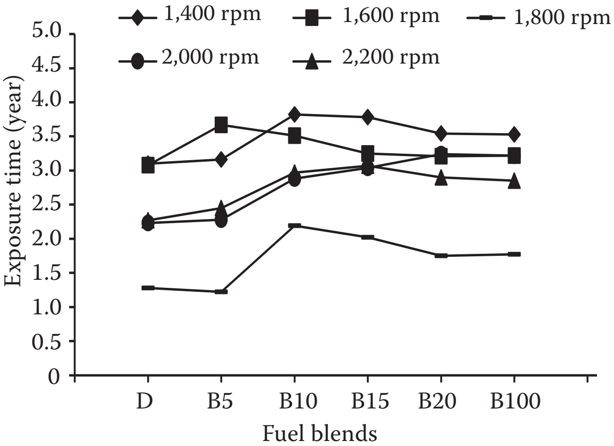

Fig. 5. Reciprocal effect of engine speed and fuel blend on exposure time

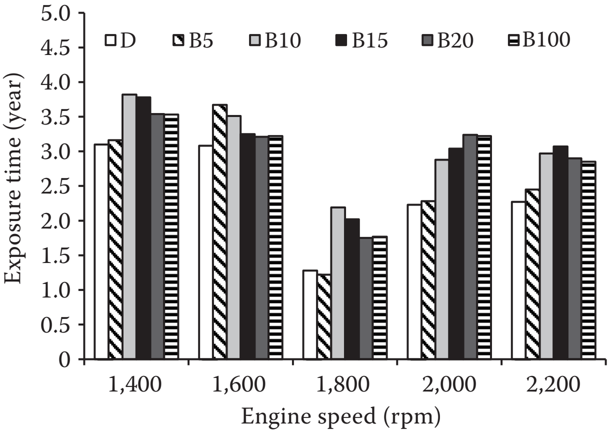

Fig. 6. Exposure time in different engine speeds

Fig. 6 shows that the vibration exposure time is decreased by increasing the engine speed, and the exposure time is decreased significantly in 1,400, 1,600, 2,000 and 2,200 rpm. Just one exception exists and that was 1,800 rpm engine speed, the reason was vibration intensification that happened in this speed and the handle had severe vibration so it reduced the exposure time severely. The max. of exposure time happened in engine speed of 1,400 rpm and the min. happened in 1,800 rpm. The max. of exposure time in 1,400 rpm of engine speed happened in biodiesel 10% and 15%. The min. of exposure time in 1,800 rpm of engine speed happened in biodiesel 5% and pure diesel. So using the engine speed of 1,800 rpm may cause damage to operators health and put them into high risk of inducing White Finger Syndrome. The best engine speeds are 1,400 and 1,600 rpm but unfortunately farmers force to use the power tiller in high speed engines to decrease their efficiency; comparing between two speeds of 2,000 and 2,200 rpm, the engine speed of 2,000 rpm seems to be more appropriate. In this engine speed using the biodiesel 15% and 20% and pure biodiesel seems appropriate.

DISCUSSION

Magnitude of vibration in power tiller depends on the location of measurement, axes, engine speed, fuel and the operator exposure time is af-

Table 5. Vibration exposure time on different fuel blends

No.	Fuel blends	Exposure time mean square (year)	Duncan method analysis (from most to least – A to F)
1	B10	3.078	A
2	B15	3.031	B
3	B20	2.934	C
4	B100	2.923	D
5	D	2.921	E
6	B5	2.577	F

fected by the vibration magnitude so it depends on engine speed and fuel blends.

The comparison between the effects of engine speeds, Table 5 showed that the vibration exposure time is decreased by increasing the engine speed, and the exposure time is decreased significantly in 1,400, 1,600, 2,000 and 2,200. Just one exception exists and that was 1,800 rpm engine speed and the exposure time in this engine speed is the least.

The comparison between the effect of different fuel blends on exposure time (Tables 5 and 6) showed that the safest fuel blend (from the point of long exposure time) is biodiesel 10%, 15% and 20%.

Previous investigations concluded that human beings are affected mentally, physically and socially by excessive vibration levels. Vibration exposure to the hand often produces various disorders like, neurological, musculoskeletal, bone, joint and vascular disorders (Griffin 1996; Griffin et al. 2003; Mansfield 2005; Dewangan, Tewari 2009). In investigations regarding the ergonomic conditions of power tiller, ten operators were studied. The study revealed that vibration of power tillers played an important role in damages experienced the operators (Dewangan, Tewari 2008, 2009). Dewangan and Tewari (2009) predicted the latency period for appearance of vibration-induced white finger to be less than 6 year in three modes of transportation, rota-tilling and rota-puddling.

No research has been done on the effect of biofuel blends on vibration of power tiller and the operator exposure time. The effect of other engine parameters on tractor such as torque, fuel consumption, power and exhausts was observed by Zenouzi (2007). Figs 5 and 6 show that B5 and B10 blends have the best performance and the lowest specific fuel consumption. B20 has high power and B25 has high torque. Therefore the same research should be done on power tiller, and the other parameters of power tiller should be considered to judge about the best blends of diesel and biodiesel.

CONCLUSION

– The working conditions of the power tiller operator fall into the highest class of risk according to ISO 5349-2 and in less than 4 years white finger may have induced in 10% of operators.
– Results of the experiments revealed that the exposure time decreases with an increase in engine speed and the level of speed has a significant effect of vibrations introduced to operator body, however, the most vibration acceleration was produced in 1,800 and 2,200 rpm.
– Vibration intensification happened in handle of power tiller in 1,800 rpm engine speed and the handle had severe vibration so it reduced the exposure time severely.
– The latency period for the appearance of vibration-induced White Finger Syndrome in biodiesel 10%, 15% and 20% respectively, so using diesel fuel can be replaced by these three kinds of fuel in power tillers.

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Received for publication August 5, 2012
Accepted after corrections January 7, 2013

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