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Field evaluation of a vibrating dual bent-share cultivator

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Abstract: In this research, the suitability of a vibrating dual bent-share cultivator was studied. Therefore, an eccentric pin-slider mechanism was designed to vibrate the two shanks laterally, using a tractor power take-off. The present study investigates the field performance of the vibrating dual bent-share cultivator with three different vibration frequencies (0, 0.88, and 2 Hz) in a clay loam soil at two working depths (100 and 200 mm) and having a water content of a 0.7 or 0.9 plastic limit. The lowest values of the draught, specific draught, and MWD were recorded at a vibration frequency of 2 Hz and a working depth of 100 mm. The draught force, specific draught, and MWD of the non-vibration implement were reduced by using a vibration frequency of 2 Hz. The coefficient of determination and *F*-values proved that the vibration frequency was more effective than the soil water content and the working depth on the draught, specific draught, and MWD. Although a dual bent-share cultivator needs low energy compared with a mould-board plough, the vibration of the dual bent-share cultivator may be recommended as an efficient energy-demanding implement in the soil manipulation process.

Keywords: bentleg; oscillatory tillage; specific draught; soil loosening; vibration

Vibratory tillage is a concept in which the tillage tools can oscillate in a particular mode of oscillation. The oscillating tools have several advantages when compared to passive tillage tools. The vibration could effectively reduce the draught force of the tools. Various studies have reported that oscillating tools require 50 to 60% less draught force compared with non-oscillating ones (Rao, Chaudhary 2018). However, there are conflicting reports regarding the total power requirement of the vibrating tillage implements. Soil fragmentation increases with the oscillating tool frequency, and the size of the soil fragments has found to be a function of the velocity ratio of the carrier and vibrating tool (Niyamapa, Salokhe 2000). Moreover, the draught force and fuel consumption are reduced as compared to the non-vibration machine (Xirui et al. 2016).

Most investigations focused on the application of the vibration on the tool draught reduction and did not consider its effects on the soil pulverisation and specific draught. Despite the potential of the forced vibration as a promising means for soil pulverisation and reducing the draught force, it has not yet been studied for a dual bent-share cultivator. The soil failure of a bent-share cultivator is in tension, which requires a much lower energy requirement than it would under compression, which is a characteristic of conventional tillage tools, in which soil failure occurs under shear. Moreover, the soil has little or no tensile strength (Harrison 1988). An increase in the cross-sectional area of the disturbed soil leads to a decrease in the specific draught, thereby enhancing the efficiency of the tillage (Mckyes, Maswaure 1997; Esehaghbeygi et al. 2005).

A reduction in draught force is the most critical performance indicator of vibrating tools. However, a tractor's body vibrates severely from the fluctuating soil cutting forces acting on the vibrating tools (Sakai et al. 1993). The ratio of the tool vibration speed to the tractor forward speed is a significant

https://doi.org/10.17221/49/2020-RAE

criterion on the effectiveness of a vibrating tool on the soil failure (Equation 1):

$$\lambda = \frac{\alpha\omega\cos\beta}{V_t} \quad (1)$$

where: λ – the velocity ratio; V_t – the tractor forward speed ($m \cdot s^{-1}$); α – the tool-tip oscillation amplitude (m), ω – the tool angular velocity ($rad \cdot s^{-1}$); β – the tool oscillation angle (°).

Butson and Macintyre (1981) reported no draught reduction when λ was less than one. In other words, the reduction of the draught force could be achieved by a vibrating mechanism, when the maximum velocity of the vibration is significantly more than the tractor forward speed. So, the cutting tool-tip moves backward relative to the soil during part of each cycle. Therefore, as the velocity ratio increases, the average draught force decreases. In addition, Bandalan et al. (1999) reported that a draught force of vibrating subsoilers decreased rapidly when the velocity ratio increased to 2.25. When compared to the non-vibration mode, the draught force of the vibrating subsoiler reduces significantly, but the total power requirement increases (Karoonboonyanan et al. 2007). However, Shahgoli et al. (2010) stated that tillage equipment needs the least power consumption at a vibration frequency of 3.3 Hz, which is 26% lower than that of the non-vibration frequency.

Previous research revealed that the vibratory tillage could increase the soil fragmentation, decrease the tool draught force and the soil bulk density. Thus, there is considerable potential for using vibratory tillage implement. Therefore, the objective of the present research was to evaluate the effectiveness of applying vibrations to a dual bent-share cultivator on the draught force, specific draught, and MWD reduction.

MATERIAL AND METHODS

The purpose of the present experiment was to study the effect of applying vibrations at different frequencies to a dual bent-share cultivator on its field performance. Also, the results of an added vibratory motion at two frequencies and constant amplitudes on the tool draught force and soil properties are studied. A previous study has shown, to some extent, the effect of reducing the draught force necessary in the case of longitudinal oscillations, but, in the case of transverse oscillations of a dual bent-share cultivator, the result of lowering the traction force has not yet reported. The experiments were conducted with a vibrating dual bent-share cultivator on a real scale with a 120 mm soil disturbance overlap based on the sideway failure zone reported by Salar et al. 2013 (Figure 1).

The descriptions of the two bent-share combinations are the same. The experimental tools were designed with a rake angle of 15º (the angle of the leading edge), a bent angle of 10º (the angle of the trailing edge), a shared length of 350 mm (perpendicular to the moving direction), and a share width of 110 mm. Therefore, the oscillation angle in Equation 1 in this forward blade dual bent-share cultivator would be minimal due to the position of the tool-tip relative to the pivot point. The shank and share of the tools were manufactured from a Ck45 steel plate with a 10 mm thickness. A crank follower mechanism is used to provide the tool oscillation. A pin-slider device with an eccentric pin on its disk is used to transform the rotational motion into a reciprocating motion (Figure 2).

The eccentricity of the pin from the disk centre was 25 mm; it means the lateral amplitude domain was 50 mm. According to Figure 1, the soil failure planes at the vibrating dual bent-share cultivator were generated from the outer cutting edge of the blade. Therefore, the reciprocating tool motion was perpendicular to the tractor motion, so two slider bearings on an upper pivot were used to support the tools (Figure 2). Another pivot rod with two slider bearings was used to prevent the rotation of the tools around the top pivot rod. In addition, to avoid the vibration of the gearbox's output shaft, a dual bearing in a unique bushing was used. The diameter of the upper and lower shafts was calculated as 30 and 20 mm, based on the bending stress (10.11 $kg \cdot mm^{-2}$) and torsional stress (5.60 $kg \cdot mm^{-2}$) on the vibrating dual bent-share cultivator according to a previous study by Salar et al. (2013).

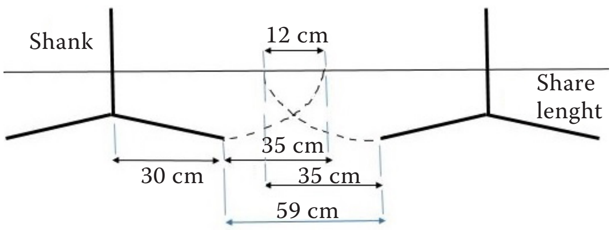

Figure 1. The overlap of the soil failure zone for the tool spacing of the vibrating dual bent-share cultivator

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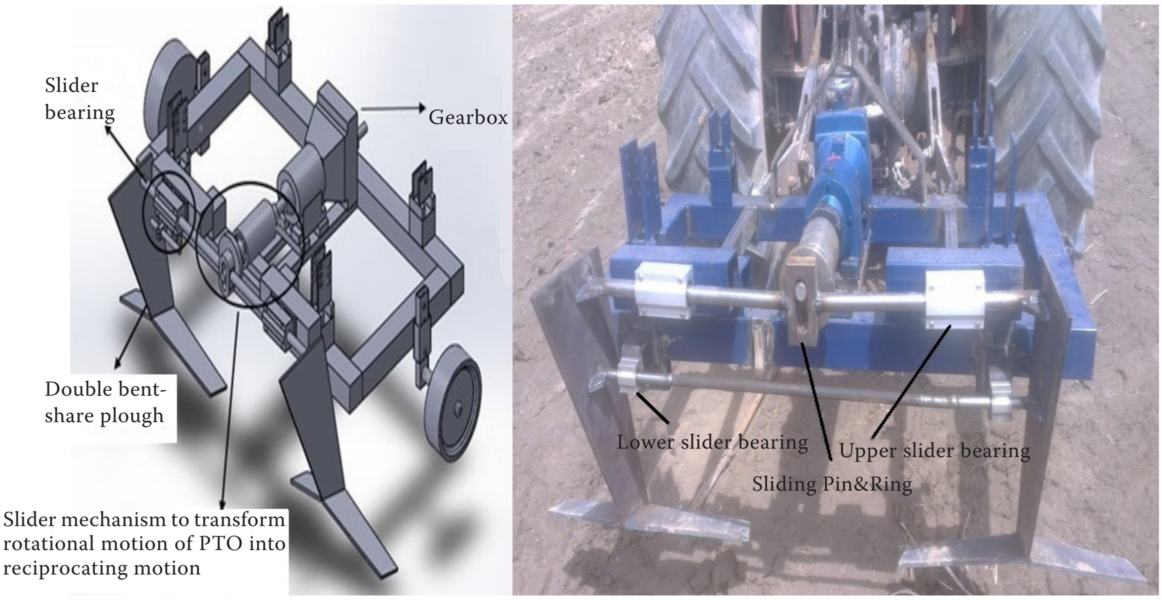

Figure 2 . Overview of the vibrating dual bent-share cultivator

The field experiments were conducted using a spilt-plot factorial in a randomised complete block design in three replicates at the Research Farm of Isfahan University of Technology (central Iran). The field had barley stubble residuals remaining from the previous farming season. The field was divided into equal parts, with each part further divided into plots based on the split-plot experiment. The plots, 3 000 mm wide and 50 000 mm long, were inside each block. An extra distance was left free between the blocks in order to measure the tractor-rolling resistance and its turning at the end of plots. The tractor forward speed was set at a meagre value of 280 mm s^{-1}; Guillen-Sanchez et al. (2017) stated that no significant difference was found in the measured parameters when the tractor speed was increased from 420 to 690 m·s^{-1}. The draught force, specific draught, cross-sectional area of the disturbed soil, and MWD were measured during and after the tillage operations. A control test with a non-vibration tool at the same working depths was also performed. The tractor was connected with the tools, but the PTO (power take-off) shaft was not connected to the spline-shaft.

The field performance of the dual bent-share cultivator was evaluated in non-vibration and vibrating modes with two vibration frequencies of 0.88 and 2 Hz, working at two depths of 100 and 200 mm, and the soil water contents of 0.7 and 0.9 of the plastic limit (PL). The plastic limit of a soil is the moisture content, which can be expressed as a percentage of the weight of the oven-dried soil, at the boundary between the plastic and semisolid states of consistency. Therefore, according to Equation 1, the ratio of the linear speed of the vibrating tool-tip to the tractor forward speed (velocity ratio) was more than one for the two vibration frequencies. The soil gravitational water content and its texture (from 0–300 mm soil layer) were determined using the oven drying method and the hydrometric method (Klute 1986), respectively, while the soil plastic limit was determined according to American Society of Testing and Materials (ASTM) guidelines (1996). The soil bulk density, cohesion, adhesion, internal, and external friction angle were also measured. The bulk density was determined by the dry mass of the soil divided by the soil volume sample. A bulk density sampling cylinder, 52 mm in diameter and 50 mm in height, was used to measure the bulk density at the soil depth of 0–50, 50–100, 100–150, and 150–200 mm, along the tool movement path due to the soil loosening from the tillage (Horn, 1988). The soil cohesion is the component of the shear strength of the soil particles that is independent of the inter-particle friction. The abilityof a unit of soil to withstand shear stress can be defined as the internal friction angle. The external friction angle or the angle of the wall friction can be defined as the angle between the abscissa and the tangent of the curve representing the relationship of the shearing resistance to the normal stress acting between the soil and the surface of another material. The definition of the sticky point can be defined to understand the adhesion of the soils to a steel surface. A direct shear

https://doi.org/10.17221/49/2020-RAE

test was used to measure the soil cohesion and internal friction angle. A Mohr-Coulomb envelop line was drawn using Microsoft Excel (2010) by applying 2.5, 3.75, and 5 kPa vertical pressures at a loading rate of 1 mm s^{-1} (Fredlund et al. 2012).

The draught force of the implement was measured according to the Regional Network for Agricultural Machinery (RNAM) test method using a 50-kN drawbar dynamometer connected between two tractors. An F204TP00K drawbar load cell model (Hosting Co., England) with capacity was used. The data monitoring was undertaken using a TR-200 screen with an accuracy of 100 N. The load cell calibration was performed using a standard Instron Testing Machine, model H25KS (Hansfield Co., England). The loading force was 5 and 45 kN at three replications. The drawbar dynamometer was attached between two tractors. The driving tractor pulled the carrier (rear tractor) that was carrying the tillage tool. In addition, the rolling resistance of the rear tractor without tools was measured. The cross-sectional area of the disturbed soil was measured using a profile meter. In order to measure the mean weight diameter (MWD) of the disturbed soil, 5-kg samples were manually collected from a soil layer of 0–200 mm, with special care to avoid the soil clod break up. A 0.5 × 0.5 m frame was used to surround the soil samples, which were then air-dried for 24 hours. The MWD of the soil clods was measured. Then, the dried soil samples were passed through 10 sieves with mesh openings of 2, 3.35, 4.76, 6.35, 12.7, 19, 25.4, 38.1, 50.8, and 76.2 mm. The mesh openings were chosen based on the clod diameters. The soil retained on each sieve was weighed, and then the MWD was calculated (Kemper and Chepil 1995). The MINITAB software (version 16) was used for the statistical analyses. The means were compared using the least significant difference (LSD) test at a 5% significant level.

RESULTS AND DISCUSSION

The soil texture was clay-loam containing 38% clay, 20.2% sand, and 41.8% silt (fine-loamy, mixed, thermic typic haplargids consisting of Kaolinite, Palygorskite, Illite, Chlorite, and Quartz). Some of the soil properties are given in Table 1.

Table 1. Some soil properties at two water contents

Property	0.9 PL	0.7 PL
Cohesion (kPa)	4.57	3.6
Adhesion (kPa)	2.29	3.61
Internal friction angle (°)	26.2	35.1
External friction angle (°)	21.4	23.4
Dry bulk density, g·mm^{-3}	1 340	1 340
Water content, d.b. (%)	17.8	13.6

PL – plastic limit

The ANOVA revealed a significant effect of the vibration frequency on the draught force of the vibrating dual bent-share cultivator. When decreasing the vibration frequency from 2 to 0.88 Hz, the draught increased by 40% (Table 2). The tractor wheel-slip values for the non-vibration and vibrating with 2-Hz frequency were 15 and 10%, respectively. The influence of the vibration is equivalent to the action of an additional force applied to the tool, which influences the draught force and friction forces between the working tool and the soil (Li et al., 2012). In similar research studies, a decrease in the vibration frequency (0.93 to 0.63 Hz) caused the draught to increase, they stated that using a higher frequency caused more soil loosening (Niyamapa and Salokhe 2000). Moreover, Shahgoli et al. (2010) reported that there was an optimal frequency near 3.3 Hz (a speed ratio of 1.5), which minimised the total engine power required to operate a subsoiler. Osman and Zhang (2013) reported a reduction in the draught force and soil bulk density compared with the non-oscillating subsoiler. Studies on the application of the oscillating subsoiler resulted in a draught reduction by up to 60% (Sakai et

Table 2. Effect of the vibration frequency, soil water content and working depth on the draught force of the vibrating dual bent-share cultivator

	Draught force (kN)
Frequency (Hz)	
0.0	6.38[a]
0.88	5.37[b]
2	2.22[c]
Soil WC (PL)	
0.7	3.59[b]
0.9	4.00[a]
Working depth (mm)	
100	2.99[b]
200	4.61[a]

the mean values for each factor with the same letter have no significant differences based on the LSD test at a 5% probability level; PL – plastic limit

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al. 1993; Niyamapa, Salokhe 2000). Slattery and Desbiolles (2003) stated that the draught force of a vibratory tillage implement could be reduced by 30 to 80%. Several experiments confirmed that the draught force for tools in an oscillating mode decreased, but in some cases, the tractor power requirement increased (Radite et al. 2010).

As the soil water content was increased from 0.7 to 0.9 of the PL, the draught increased significantly by 11% (Table 2), but previous researchers reported that soil cutting is easier in moist soils (Dexter, Bird 2001; Sanchez-Giron et al. 2005). The vibrating tool fractures the dry soil and reduces the draught force, such as the increased peak stresses due to the vibration and the increase in the particle kinetic energy (Linde 2007). An increase in the soil water content has been reported to enhance the soil particle integration and cause a coarse aggregate, thereby expanding the surcharge and draught forces (Dexter, Bird 2001).

The effect of the working depth on the draught force was significant. The draught force was increased by 54% when the working depth was increased from 100 to 200 mm. The same trend was reported in the draught force when the working depth increased from 300 to 400 mm (Guillen-Sanchez et al. 2017). The increase in the draught force is due to the higher soil surcharge pressure as well as the increase in the soil-metal friction (Mckyes, Maswaure 1997). It seems that the effect of the vibration frequency on the draught force was more effective than the working depth based on the coefficient of determination and the F-values (Table 3). Only the interaction between the working depth and vibration frequency was significant on the draught force (Figure 3).

The analysis of variance revealed that the effect of the vibration frequency and working depth on the cross-sectional area of the disturbed soil was significant. The cross-sectional area of the disturbed soil perpendicular to the direction of the travel increased with the increasing vibration frequencies and the working depth of the cultivator by 6 and 112%, respectively (Table 4). This result is in line with work reported by other researchers (Biris et al. 2016). It seems that working depth was more effective than the soil water content and vibration frequency on the cross-sectional area based on the coefficient of determination (Table 5).

According to Figure 4, the effect of the interaction between the vibration frequency and the working depth, soil water content, and working depth on the cross-sectional area of the disturbed soil

Table 3. Coefficient of determination and F-values of the draught force of the vibrating dual bent-share cultivator

	Working depth	Soil water content	Vibration frequency
F-value	1 210.26	79.03	4 578.08
R^2 (%)	15.16	0.98	57.35

R – coefficient of determination

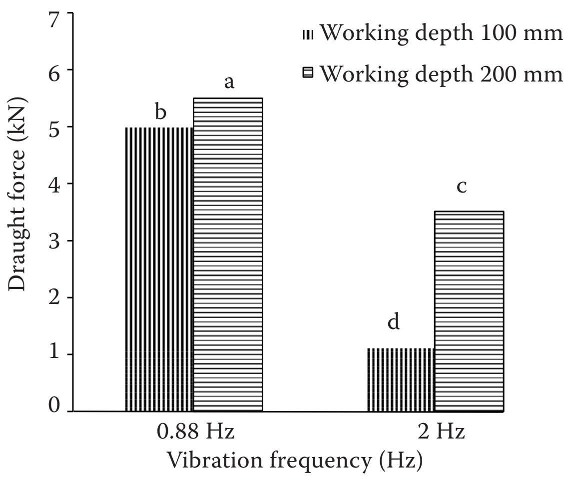

Figure 3. The interaction between the vibration frequency and the working depth on the draught force of the vibrating dual bent-share cultivator

The same letters have no significant differences based on the LSD test at a 5% confidence level.

Table 4. Effect of the vibration frequency, soil water content and working depth on the cross-sectional soil area of the vibrating dual bent-share cultivator

	Cross-sectional area (mm^{-2})
Frequency (Hz)	
0.0	127 650^{b}
0.88	135 480^{b}
2	143 950^{a}
Soil WC (PL)	
0.7	138 880^{a}
0.9	140 550^{a}
Working depth (mm)	
100	894 650^{b}
200	189 960^{a}

the mean values of the experimental variable in each row that have the same letters have no significant differences based on the LSD test at a 5% confidence level; PL – plastic limit

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Table 5. Coefficient of determination and *F*-values of the cross-sectional soil area of the vibrating dual bent-share cultivator

	Working depth	Soil water content	Vibration frequency
F-value	38 428.9	10.58	273.27
R^2 (%)	98.95	0.027	0.7

R – coefficient of determination

was significant (Figure 4). The cross-sectional area mostly increased with an increase in the variables. The cross-sectional area has reportedly shown an excellent response to an increasing operation depth (Mckyes, Maswaure 1997; Aday, Ramadhan 2019).

The analysis of variance showed not only the vibration frequency, but also working depth, and their interaction had a significant effect on the specific draught. In contrast, the soil water content did not have a significant impact. The specific draught decreased with an increase in both the vibration frequency and working depth (Table 6). It seems that the vibration frequency was more effective than the working depth on the specific draught based on the coefficient of determination and *F*-values (Table 7). By increasing the working depth from 100 to 200 mm, it was found that the increase in the soil disturbance area was higher than that of the draught, which led to a lower specific draught. It is in line with the results reported by others

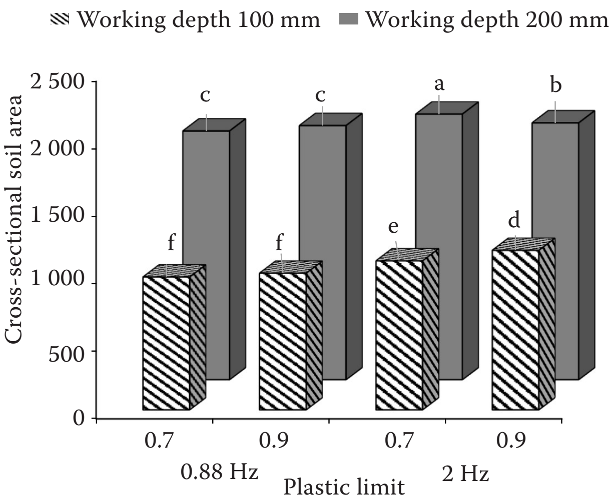

Figure 4. The frequency of the vibrating dual bent-share cultivator for the soil water content and working depth interaction on the cross-sectional area of the disturbed soil

the same letters have no significant differences based on the LSD test at a 5% confidence level; PL – plastic limit

Table 6. Effect of the vibration frequency, soil water content and working depth on the specific draught of the vibrating dual bent-share cultivator

	Specific draught (kN·m^{-2})
Frequency (Hz)	
0.0	51.6[a]
0.88	44.63[b]
2	14.08[c]
Soil WC (PL)	
0.7	28.16[a]
0.9	30.56[a]
Working depth (mm)	
100	34.28[a]
200	24.44[b]

the mean values of the experimental variable in each row that have the same letters have no significant differences based on the LSD test at a 5% confidence level; PL – plastic limit

Table 7. Coefficient of determination and *F*-values of the specific draught of the vibrating dual bent-share cultivator

	Working depth	Soil water content	Vibration frequency
F-value	46.06	2.74	443.84
R^2 (%)	7.03	0.41	67.76

R – coefficient of determination

(Arvidsson, Hillerstrom 2010; Aday, Ramadhan 2019). Godwin (2007) was also observed that the depth of tillage influences the plough specific draughts.

The vibration frequency and working depth had a significant effect on the soil MWD, whereas the soil water content, in the range of 0.7 to 0.9 of the plastic limit, did not have a significant impact. However, the results reported by other researchers working with other tillage implements suggest that the optimum soil water content for soil fragmentation during tillage is near the lower plastic limit of 0.9 (Hemmat et al. 2007). The results also showed that the soil MWD, at a higher vibration frequency, was lower because of the higher energy input (Table 8). It seems that the vibration frequency was more effective than the working depth on the specific draught, based on the coefficient of determination and the *F*-values (Table 9). When increasing the working depth from 100 mm to 200 mm, the MWD was increased. However, some researchers stated that the MWD decreased when increasing the working depth (Rattan 2008).

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Table 8. Effect of the vibration frequency, soil water content and working depth on the MWD of the vibrating dual bent-share cultivator

	MWD (mm)
Frequency (Hz)	
0.0	19.30[a]
0.88	17.93[b]
2	15.71[c]
Soil WC (PL)	
0.7	16.6[a]
0.9	17.04[a]
Working depth (mm)	
100	15.82[b]
200	17.81[a]

the mean values of the experimental variable in each row that have the same letters have no significant differences based on the LSD test at a 5% confidence level; PL – plastic limit; MWD – mean weight diameter

Table 9. Coefficient of determination and *F*-values of the MWD of the vibrating dual bent-share cultivator

	Working depth	Soil water content	Vibration frequency
F-value	4.62	0.23	5.76
R^2 (%)	44.09	7.27	79.63

R – coefficient of determination

CONCLUSION

The results of the present study revealed that inducing a vibration at a 2 Hz frequency to a dual bent-share cultivator significantly decreases the specific draught and clod MWD. The decrease in the specific draught was due to a decrease in the draught force by a factor of 1.9, and an increase in the soil-disturbed area by 13%. The smaller clod size during the soil disturbance with the vibrating cultivator was due to the more effective energy transfer to the soil.

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