Scrutinization of overall energy efficiency of machinery in plowing process

Seyed Mojtaba Shafaei*, Mohammad Loghavi, Saadat Kamgar

(Department of Biosystems Engineering, School of Agriculture, Shiraz University, Shiraz 71441-65186, Iran)

Abstract: This work was dedicated to describe overall energy efficiency of machinery in plowing process as affected by some operational variables of plowing depth (10-30 cm) and forward speed (2-6 km/h). To achieve this aim, field trials in clay loam soil in southern region of Iran were performed by means of disk plow implement and front wheel assist tractor. The effects of the operational variables on the efficiency were examined. General two-variable linear and quadratic equations were fitted to obtained field data in order to model the efficiency with respect to plowing depth and forward speed. The results demonstrated that the individual effect of plowing depth on the efficiency was more dominant (1.2 times) than that of forward speed. Meanwhile, the compounded effect of plowing depth and forward speed on the efficiency was prevailed (4 and 3.2 times) than that of the individual effect of forward speed and plowing depth, respectively. The satisfactory results drawn from fitness of the quadratic Equation on data rather than the linear Equation manifested nonlinear increasing variations of overall energy efficiency as influenced by augmentation of plowing depth and forward speed. The condensed analytical information in conjunction with modeling results disseminate knowledge in usable and useful form to farmers, associated policy division, and stakeholders.

Keywords: energy requirement; fuel consumption; tractor drawbar power; implement draft force

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1 Introduction

Mechanical energy obtained from fuel in agricultural machinery is consumed for several targets. Machinery movement and field operations are two main components of these targets. In this context, a minor portion of the energy is wasted by unavoidable rolling resistance force and slip of wheels (Shafaei et al., 2021a; Shafaei et al., 2021b). A major portion of the energy is converted to gross traction forces of wheels. Total gross traction forces can be used as drawbar force. In case of tractor, drawbar force can be devoted for pulling of implement. Quantity of drawbar force required for pulling of implement presents proportionality between size of implement and tractor power. This proportionality is numerically ascertained for machinery on the basis of performance parameter of overall energy efficiency. Accordingly, it can be stated that the efficiency of machinery can be assistive in relative assessment of energy which is dissipated or applied.

In plowing process with specific machinery, there are several operational variables affecting machinery performance such as soil texture and moisture content, forward speed, plowing depth, and tractor mode (two-wheel drive and four-wheel drive). Hence, taking these operational variables into considerations for assessment of

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* **Corresponding author: Seyed Mojtaba Shafaei,** Ph.D., Department of Biosystems Engineering, School of Agriculture, Shiraz University, Shiraz, Iran. Email: smshafaei@shirazu.ac.ir.

machinery performance in plowing process is vital to gain comprehensive outlook about favorable performance parameters.

Literature review concluded a considerable number of previous works conducted over the world in the past four decades has dealt with studying of overall energy efficiency of machinery in various processes (Jr, 1985; Jr, 1989; Souza et al., 1991; Smith, 1993; Souza et al., 1994; Kheiralla et al., 2004; Serrano et al., 2009; Karparvarfard and Rahmanian-Koushkaki, 2015; Ranjbarian et al., 2017; Shafaei et al., 2019a; Shafaei et al., 2019b; Shafaei et al., 2019c; Askari et al., 2022). The main findings of the previous works partially elucidated the effect of some operational variables on the efficiency. However, some challenges are not still responded in this regard.

Although the previous works have described some aspects of overall energy efficiency of machinery, less attention has been given by the researchers to ascertain simultaneous effect of plowing depth and forward speed on the efficiency. Hence, there is currently not enough technical information regarding this phenomenon and thereby, knowledge about impact of the variables on the efficiency is still incomplete. For the first time, response to the lack in literature coincides with point of interest in this study. Therefore, this study contributes to cover following items:

(1) Carrying out statistical analysis in order to determine significance of the individual/compounded effect of operational variables (plowing depth and forward speed) on the efficiency.

(2) Ascertaining statistical significance of the effect of levels of the operational variables on the efficiency.

(3) Comparing quantity of the effect of individual/compounded effect of the operational variables on the efficiency.

(4) Assessing prognostication ability of general two-variable linear and quadratic equations for modeling of the efficiency based on multiple input variables (plowing depth and forward speed).

2 Research methodology

2.1 Field layout

An experimental area with clay loam soil texture and flat topography in Bajgah Research Station of Shiraz University was considered as tillage site. The site was partitioned into 27 plots (30×5 m) for performing of trials. Prior to the trials, 30 cm topsoil layer was tested at five random locations utilizing a cylindrical core sampler. The obtained samples were immediately packed in separate polyethylene bags and transferred to research laboratory. To ascertain moisture content of soil, the samples were dried in a convection oven at 105±1 ℃ until constant weight was gained (SAA, 1977). To ensure repeatability and reliability of collected data, each test type was replicated thrice. The moisture content as well as bulk density of the soil were found to be 8.84±1.05% d. b. and 1.23±0.17 g cm^{-3}, respectively.

2.2 Machinery specifications

A front wheel assist tractor and mounted-type disk plow implement were used as machinery. Some technical and commercial specifications of the tractor and implement are given in Table 1.

To measure some performance parameters (fuel consumption and draft force) of the machinery, the tractor was fully equipped with an instrumentation system. The developed system was generalized for agricultural machinery in a previous work (Shafaei et al., 2019d). Technical specifications and engineering considerations of the system have been fully described in the work. The system composed of a data acquisition unit and two groups of transducers (two flow meters and one load cell).

Table 1 Some technical and commercial specifications of the machinery used in this study

Type	Model	Manufacture	Country	Specifications
Tractor	MF-399	ITM	Iran	81 kW maximum power at rated speed of engine and 39.34 kN total weight
Disk plow implement	TAKA 165	TAKA	Iran	120 cm working width and three disk bottoms with a gauge wheel

The two flow meters (model: FS300A G3/4, manufacture: Meinte, Country: China) were utilized for measuring of tractor fuel consumption. The first one was embedded between the injector pump and fuel filter of the tractor. The second one was also embedded in the line between injection pump and fuel tank and thereby, excess fuel returned to the tank was measured. Difference between two measured values obtained from the flow meters was considered as the tractor fuel consumption value.

The load cell (model: NS4-5t, manufacture: Mavin, Country: China) was used to measure required draft force of the implement in accordance with method standardized by Regional Network for Agricultural Machinery (RNAM) (RNAM, 1995). The method has been frequently used in previous works by many researchers (Jadhav et al., 2013; Moeenifar et al., 2014; Rahmanian-Koushkaki et al., 2015; Ndisya et al., 2016; Azimi-Nejadian et al., 2019; Singh et al., 2021).

Prior to field trials, initial checkout of the tractor-implement system was performed at base station. The implement was attached to the tractor using top link and lift links of the tractor. The links were adjusted together in order to level the implement and minimize parasitic forces acted on the system.

2.3 Field trials

The field trials were carried out in triplicate with the tractor in two-wheel drive mode. Levels of plowing depth (10, 20 and 30 cm) were experimentally adjusted utilizing the three-point linkage height control of the tractor in a practice area of the tillage site. In tillage site, before each main test plot, a practice area was allocated to attain level of plowing depth and forward speed. Furthermore, levels of forward speed (2, 4 and 6 km/h) were obtained by accelerating of the machinery in a known gear range at rated speed of tractor engine in the practice area. In the main test plots, fuel consumption and draft force values were completely collected for different levels of forward speeds and plowing depths utilizing the instrumentation system.

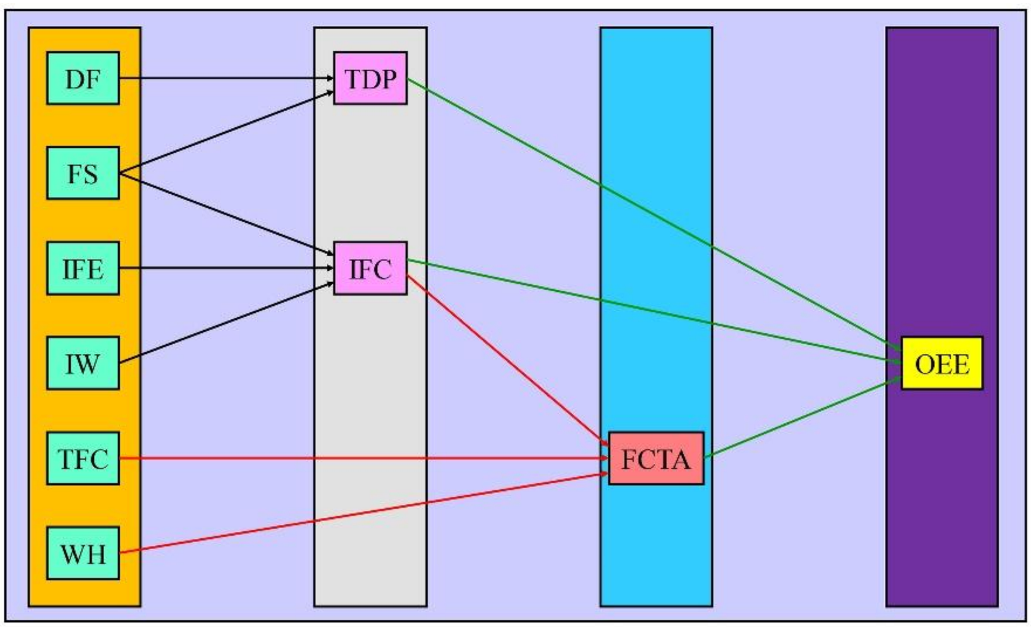

Figure 1 Graphical model for calculation of overall energy efficiency of the machinery in plowing process (DF: draft force, FS: forward speed, IFE: implement field efficiency, IW: implement width, TFC: tractor fuel consumption, WH: working hour, TDP: tractor drawbar power, IFC: implement field capacity, FCTA: fuel consumption per tilled area, and OEE: overall energy efficiency)

In each plot, draft force required for the implement was measured based on the RNAM method. According to the method, the machinery were pulled by a secondary tractor (model: 4450, Company: John Deere, Country: USA), while the load cell transducer of the instrumentation system was horizontally connected between the two tractors. During implementing of the RNAM method, it was ensured that the machinery were placed on level ground in both lateral and longitudinal directions and connection line of the transducer was parallel to ground surface. The operations were carried out with the mounted implement at desired plowing depth and forward speed. Obtained data from the transducer were considered as gross traction forces. The operations were also conducted at desired forward speed with the implement in transport position and the collected data from the transducer were considered as rolling resistance force of the tractor wheels. Finally, draft force was calculated once rolling resistance force of the main tractor was deducted from the gross traction force. It should be noted that the operations were conducted, while transmission system of the main tractor was switched off.

$$\mathrm{OEE} = \frac{3.6 \times \mathrm{TDP}}{38.7 \times \mathrm{FCTA} \times \mathrm{IFC}} \times 100 \tag{1}$$

2.4 Data processing

To describe calculation trend of overall energy efficiency of the machinery, based on required parameters, graphical model is presented in Figure 1. Data collected by the instrumentation system in the field trials were employed to calculate the efficiency based on following Equation (Jr, 1989).

Where OEE is overall energy efficiency (%), TDP is tractor drawbar power (kW), FCTA is fuel consumption per tilled area (L ha^{-1}), and IFC is implement field capacity (ha h^{-1}).

To ascertain required terms (tractor drawbar power, implement field capacity, and fuel consumption per tilled area) in the Equation 1, following equations were also employed (Renoll, 1981; ASAE, 2011)

$$\mathrm{TDP} = \frac{\mathrm{DF} \times \mathrm{FS}}{3.6} \tag{2}$$

$$\mathrm{IFC} = \frac{\mathrm{IW} \times \mathrm{FS} \times \mathrm{IFE}}{10} \tag{3}$$

$$\mathrm{FCTA} = \frac{\mathrm{TFC}}{\mathrm{IFC} \times \mathrm{WH}} \tag{4}$$

Where DF is required draft force of the implement (kN), FS is forward speed (km/h), IW is implement width (m), IFE is implement field efficiency (%), TFC is tractor fuel consumption (L), and WH is working hour (h).

2.4.1 Statistical descriptions

Statistical descriptions of overall energy efficiency of the machinery in plowing process were computed by means of some statistical indices known as mean, standard deviation, coefficient of variation, and coefficient of non-uniformity. Following equations were employed to compute the statistical indices (Shafaei and Kamgar, 2017).

$$M = \frac{\sum_{i=1}^{i=N} OEE_{act,i}}{N} \tag{5}$$

$$SD = \frac{\sqrt{\sum_{i=1}^{i=N} (OEE_{act,i} - M)^2}}{N} \tag{6}$$

$$CV = (\frac{SD}{M}) \times 100 \tag{7}$$

$$CNU = (\frac{OEE_{max} - OEE_{min}}{M}) \times 100 \tag{8}$$

Where M is mean of used data (%), N is number of used data, $OEE_{act,i}$ is ith actual value of overall energy efficiency (%), SD is standard deviation (%), CV is coefficient of variation (%), CNU is coefficient of non-uniformity (%), OEE_{max} is maximum value of overall energy efficiency (%), and OEE_{min} is minimum value of overall energy efficiency (%).

2.4.2 Statistical analysis

Statistical analysis for the individual and compounded effects of forward speed (3 levels) and plowing depth (3 levels) on overall energy efficiency of the machinery in plowing process was performed using the analysis of variance and Duncan's multiple range test methods. The methods were implemented based on completely randomized factorial design with two main treatment factors, at 1% probability level (α=0.01). Contribution of each variation to the efficiency was then calculated based on the analysis of variance results utilizing Equation 9 (Shafaei and Kamgar, 2017).

$$C_V = \frac{SSV}{SST} \times 100 \tag{9}$$

Where C_V is contribution of variation (%), SSV is sum of square of variation, and SST is total sum of square.

2.5 Mathematical modeling

General two-variable linear and quadratic equations (Equations 10 and 11, respectively) (Shafaei et al., 2017; Korany et al., 2012) were fitted to data in order to model overall energy efficiency of the machinery in plowing process regarding simultaneous changes of forward speed and plowing depth.

$$\mathrm{OEE} = \mathrm{a(FS)} + \mathrm{b(PD)} + \mathrm{f} \qquad (10)$$

$$\mathrm{OEE} = \mathrm{a(FS)} + \mathrm{b(PD)} + \mathrm{c(FS^2)} + \mathrm{d(FS \times PD)} + \mathrm{e(PD^2)} + \mathrm{f} \qquad (11)$$

Where PD is plowing depth (cm), a, b, c, d, and e are two-variable model coefficient, and f is two-variable model constant.

2.6 Assessment of fitted mathematical models

Prognostication accuracy of fitted mathematical models was assessed using some statistical indices (coefficient of determination, root mean square error, mean relative deviation modulus, and mean of absolute values of modeling residual errors). The indices were computed with help of following equations (Shafaei et al., 2016a; Shafaei et al., 2016b). Some researchers have also used these indices in their studies (Upadhyay and Raheman, 2019; Nataraj et al., 2021; Hensh et al., 2021).

$$R^2 = 1 - \frac{\sum_{i=1}^{i=N}(OEE_{act,i} - OEE_{mod,i})^2}{\sum_{i=1}^{i=N}(OEE_{act,i} - OEE_{actave})^2} \qquad (12)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{i=N}(OEE_{mod,i} - OEE_{act,i})^2} \qquad (13)$$

$$MRDM = \frac{100}{N}\sum_{i=1}^{i=N}\left(\frac{|OEE_{mod,i} - OEE_{act,i}|}{OEE_{act,i}}\right) \qquad (14)$$

$$MAVMRE = \frac{1}{N}\sum_{i=1}^{i=N}|OEE_{mod,i} - OEE_{act,i}| \qquad (15)$$

Where R^2 is coefficient of determination, $OEE_{act,i}$ is ith actual value of overall energy efficiency (%), OEE_{actave} is average of actual overall energy efficiency (%), $OEE_{mod,i}$ is ith modeled overall energy efficiency (%), RMSE is root mean square error (%), MRDM is mean relative deviation modulus (%), and MAVMRE is mean of absolute values of modeling residual errors (%).

3 Results and discussion

3.1 Statistical descriptions

Table 2 lists the statistical indices obtained for overall energy efficiency of the machinery in plowing process. With reference to the Table 2, applying forward speed of 2 km/h and plowing depth of 10 cm led to achievement of minimum value of the efficiency. Similarly, applying forward speed of 6 km/h and plowing depth of 30 cm led to reach of maximum value of the efficiency. According to the Table 2, the efficiency ranged from 7.24 to 33.10% with high values of coefficient of variation and coefficient of non-uniformity. These values express that the efficiency varied intensively as operational variables changed.

Table 2 Statistical indices obtained for overall energy efficiency of the machinery in plowing process

Mean (%)	Standard deviation (%)	Minimum (%)	Maximum (%)	Coefficient of variation (%)	Coefficient of non-uniformity (%)
21.43	7.79	7.24	33.10	36.35	120.67

3.2 Statistical analysis

The analysis of variance results for the effect of forward speed and plowing depth on overall energy efficiency of the machinery in plowing process are tabulated in Table 3. According to the Table 3, the individual and compounded effects of the operational variables on the efficiency were significant at 1% probability level ($P<0.01$). Hence, it could be inferred that the efficiency was a function of forward speed and plowing depth and therefore, two-variable model based on forward speed and plowing depth might be adequate enough for prognostication of the efficiency.

Figure 2 graphically characterizes contribution of each variation to the efficiency. According to the Figure 2, contribution of plowing depth variable to the efficiency was notably higher (1.3 times) than that of forward speed variable. Therefore, it is anticipated that the efficiency was more considerably influenced by plowing depth than forward speed.

Table 3 Analysis of variance results for overall energy efficiency of the machinery in plowing process

Source of variation	Degree of freedom	Sum of squares	Mean square	F value
Replication	2	2.112	1.056	0.230
Plowing depth (PD)	2	846.585	423.292	93.430**
Error of PD	4	19.764	4.941	1.090
Forward speed (FS)	2	636.688	318.344	70.260**
PD×FS	4	3.350	0.838	0.180**
Error of FS	12	54.369	4.531	
Total	26	1562.868		

**Significant at $P<0.01$

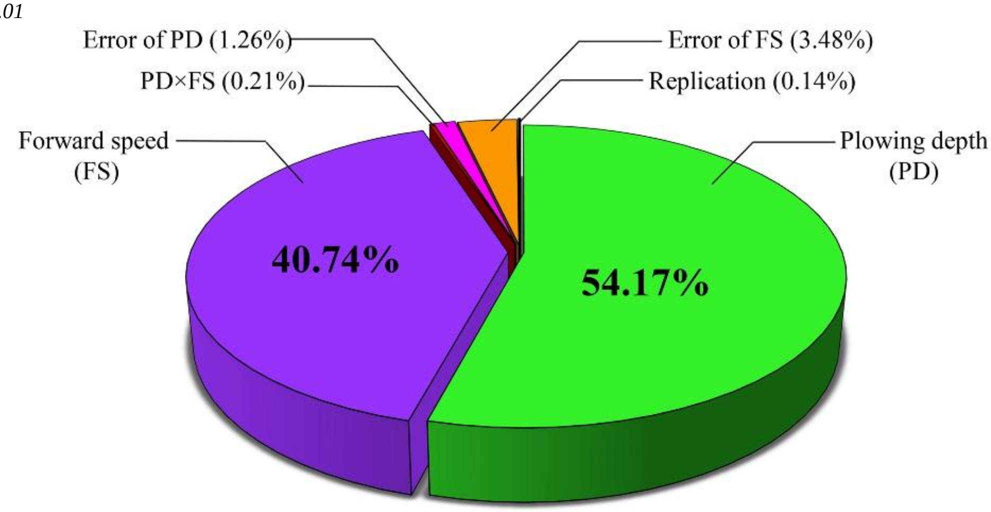

Figure 2 Contribution of variations to overall energy efficiency of the machinery in plowing process

3.3 Effect of operational variables

3.3.1 Plowing depth

The Duncan's multiple range test results for the effect of plowing depth on overall energy efficiency of the machinery in plowing process as depicted in Figure 3 indicates that increase of plowing depth from 10 to 30 cm (200%) led to remarkable increase of the efficiency (96.62%). Higher draft force required for the implement at higher plowing depth (Karmakar et al., 2009; Obermayr et al., 2011; Mohammadi et al., 2012; Akbarnia et al., 2014; Obermayr et al., 2014) results in higher tractor drawbar power, based on the Equation 1, and accordingly, augmentation of the efficiency.

3.3.2 Forward speed

The Duncan's multiple range test results for the effect of forward speed on overall energy efficiency of the machinery in plowing process as diagramed in Figure 4 shows that increasing forward speed from 2 to 6 km/h (200%) led to noteworthy increase of the efficiency (78.11%). According to the Equation 1, the efficiency is directly related to forward speed. Thus, the efficiency considerably increases due to forward speed augmentation.

3.3.3 Compounded effect

Figure 5 depicts the Duncan's multiple range test results for the compounded effect of forward speed and plowing depth on overall energy efficiency of the machinery in plowing process. Forward speed increment from 2 to 6 km/h (200%) along with plowing depth increment from 10 to 30 cm (200%) resulted in notable augmentation of the efficiency (309.99%). The compounded effect of plowing depth and forward speed on the efficiency can be physically interpreted as plowing depth changes, soil resistance might change and accordingly, forward speed could be affected as soil resistance changes and therefore, the efficiency differs. An insignificant difference among the efficiency as affected by the operational variables is denoted by the same letters in the Figure 5. Regarding energy management point of view, to reach the higher efficiency, it is suggested to alter levels of the variables with insignificant effect on the efficiency.

Preceding researcher believed that the efficiency less than 10% is attributed to poor tractive efficiency or machinery mishmash. Moreover, the range of 10-20% can be reflected as normal range. The best situation happens more than 20%. In this situation, proportionality between size of implement and tractor power is proper (Jr, 1985). According to the Table 2, the maximum efficiency of 33.10% was obtained in this research. Therefore, to achieve the higher efficiency, possibility of implement application with higher working width including more disk bottoms can be provided. Augmentation of the efficiency is effective in decrement of energy dissipation and fuel consumption.

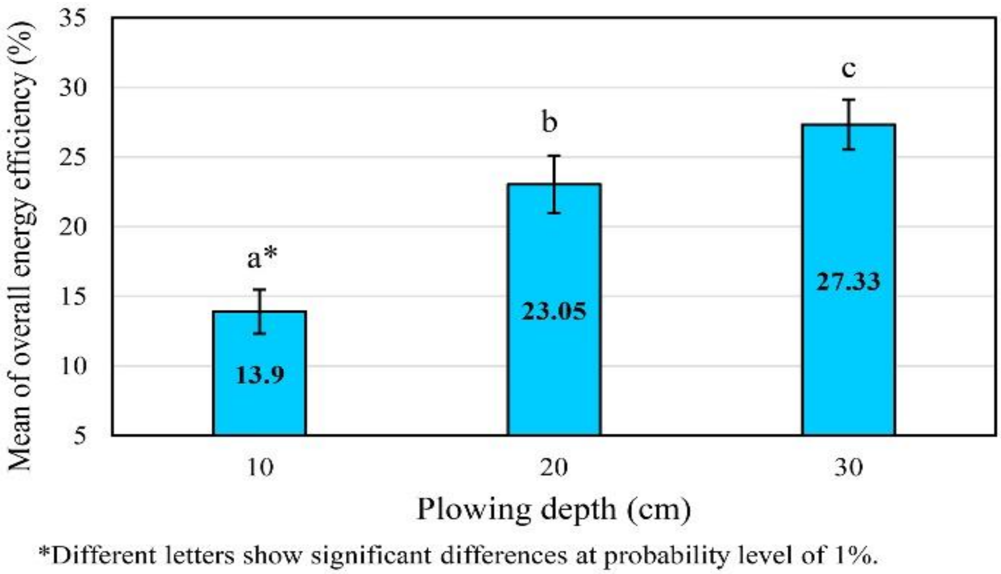

Figure 3 The Duncan’s multiple range test results for the individual effect of plowing depth on overall energy efficiency of the machinery in plowing process

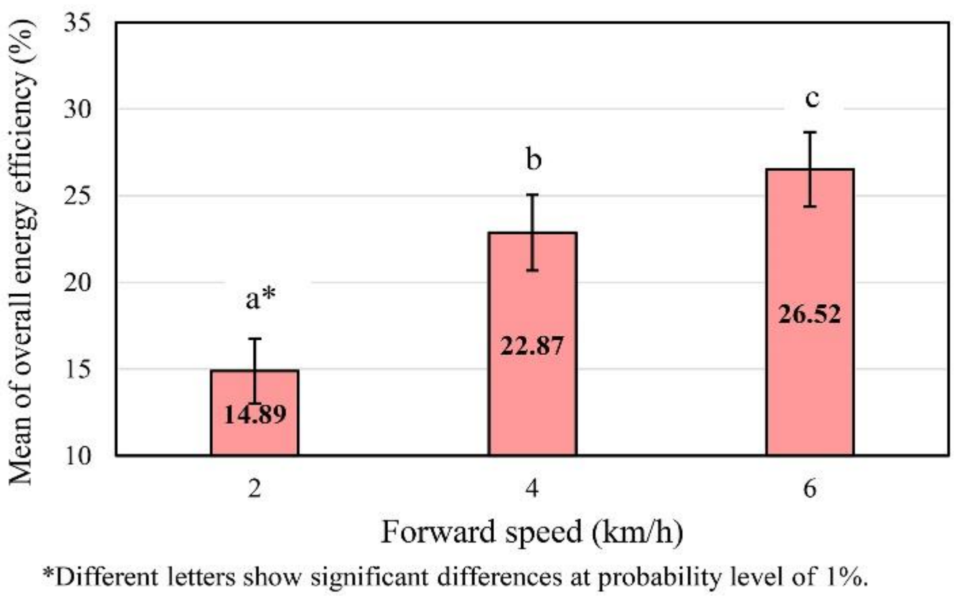

Figure 4 The Duncan’s multiple range test results for the individual effect of forward speed on overall energy efficiency of the machinery in plowing process

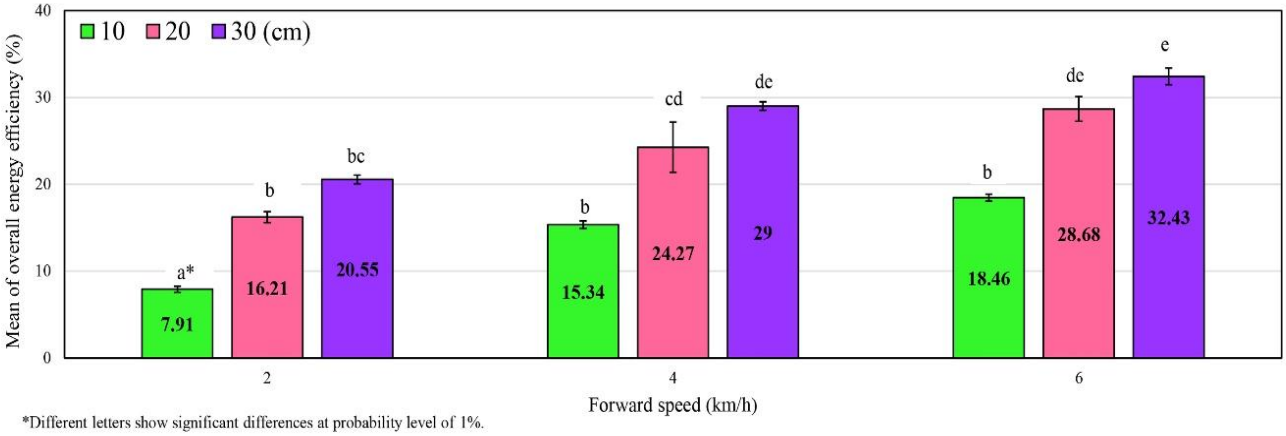

Figure 5 The Duncan's multiple range test results for the compounded effect of forward speed and plowing depth on overall energy efficiency of the machinery in plowing process

3.4 Comparison of effect of operational variables

Augmentation of overall energy efficiency of the machinery in plowing process as affected by the operational variables, obtained from comparison of the Duncan's multiple range test results, is diagramed in Figure 6. With reference to the Figure 6, it is clearly seen that augmentation of the efficiency by the compounded effect of forward speed and plowing depth was greater (4 and 3.2 times) than that of the individual effect of forward speed and plowing depth, respectively. Meanwhile, the pronounced individual effect of plowing depth on the efficiency than that of forward speed (1.2 times) was also anticipated by results of the Section 3. 2. Hence, to effectively manage the efficiency, it is suggested to apply simultaneous changes of plowing depth and forward speed, by taking desired root depth in consideration, rather than individual change of plowing depth or forward speed. Additionally, to achieve the higher efficiency and reduce energy dissipation, changes of plowing depth rather than forward speed are more effective.

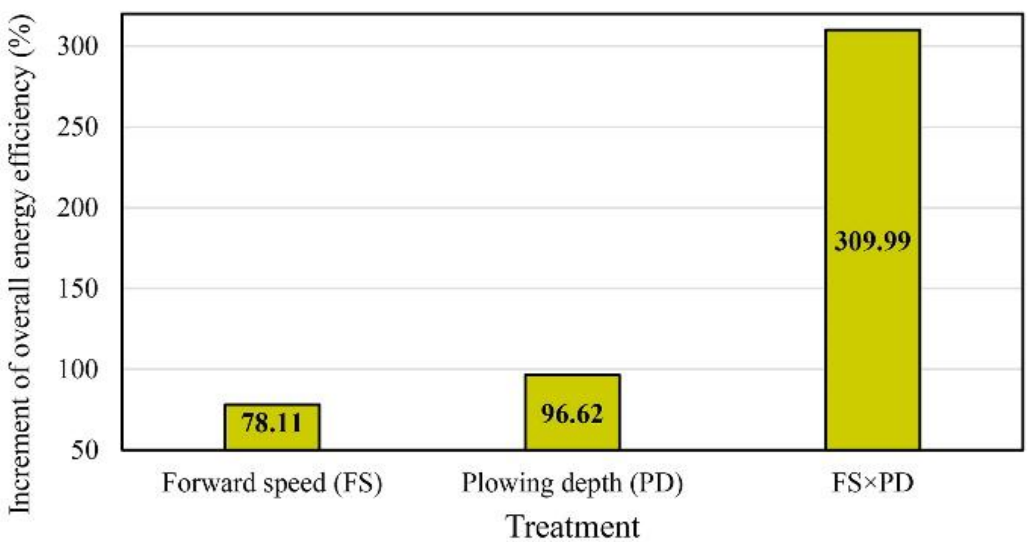

Figure 6 Overall energy efficiency increment of the machinery in plowing process as affected by the operational variables

3.5 Assessment of fitted mathematical models

The constants, coefficients, and statistical indices of mathematical models fitted to data in order to prognosticate overall energy efficiency of the machinery in plowing process, regarding to simultaneous changes of forward speed and plowing depth, are listed in Table 4. The acceptable values of coefficient of determination, root mean square error, mean relative deviation modulus, and mean of absolute values of modeling residual errors reported in the Table 4 confirm that the efficiency was more satisfactorily modeled by two-variable quadratic model than two-variable linear model. Figure 7 shows mapping between modeled and actual values of the efficiency by the fitted mathematical models. Close scattering of data points around unity slope line in the Figure 7 represents the excellent capability of the quadratic model than the linear model in prognostication of the efficiency.

Table 4 Constants, coefficients, and statistical indices of mathematical models fitted to data for prognostication of overall energy efficiency of the machinery in plowing process

Two-variable model	a	b	c	d	e	f	Coefficient of determination	Root mean square error (%)	Mean relative deviation modulus (%)	Mean of absolute values of modeling residual errors (%)
Linear	2.852	0.655	-	-	-	-3.071	0.921	2.083	10.168	1.767
Quadratic	7.677	1.664	-0.624	0.008	-0.026	-19.412	0.997	0.634	2.795	0.546

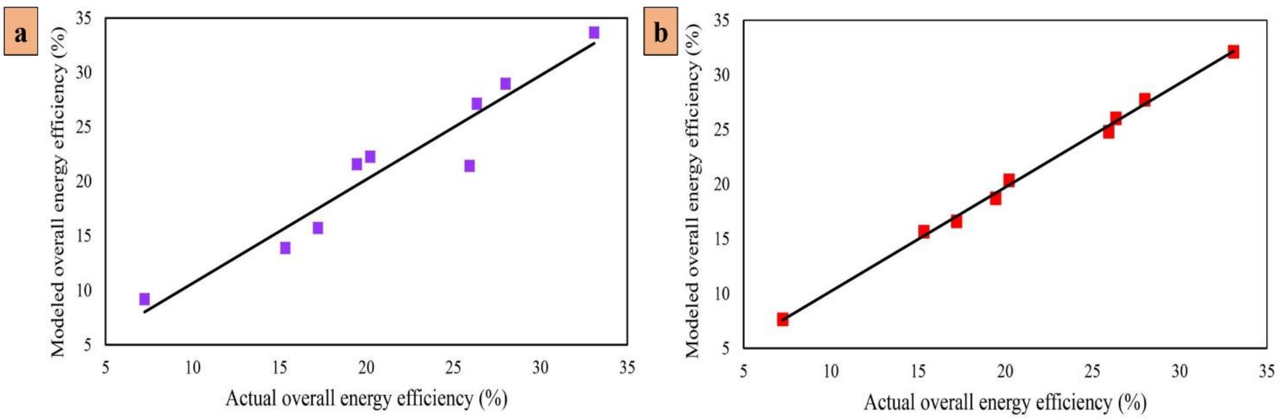

Figure 7 Mapping between modeled and actual values of overall energy efficiency of the machinery in plowing process by the linear model (a) and the quadratic model (b)

Figure 8 illustrates distribution of modeling residual errors of the mathematical models fitted for prognostication of the efficiency. According to the Figure 8, it is apparently observed that modeling residual error values randomly happened and no trend can be detected. Therefore, it is found that modeling residual error values of the mathematical models were not sensitive to actual data.

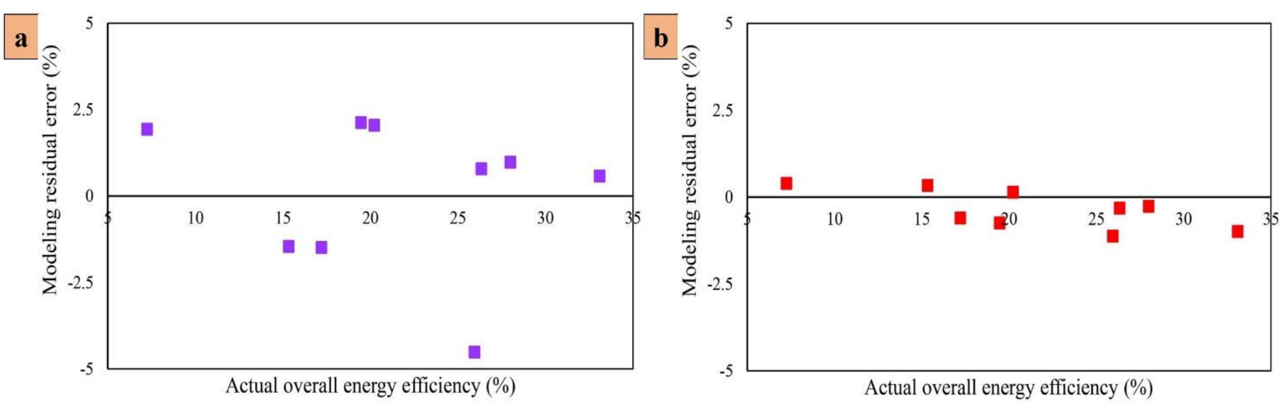

Figure 8 Distribution of modeling residual errors of overall energy efficiency of the machinery in plowing process by the linear model (a) and the quadratic model (b)

To sum up modeling results, it can be stated that two-variable quadratic model was reliable enough for direct prognostication of the efficiency of the machinery in plowing process with no need for actual measurement of tractor performance parameters required in the Equation 1.

3.6 Prognostication of overall energy efficiency

Surface plot resulted from fitting of the quadratic model to data has been drawn to study the simultaneous effect of forward speed and plowing depth on overall energy efficiency of the machinery in plowing process (figure 9a). This plot clarifies concept of how the model output responded to the input variables. It can be obviously seen in the Figure 9a that the efficiency increased nonlinearly as plowing depth and forward speed increased. Additionally, Figure 9b depicts model contour plot. The contour plot presents graphical reflection of the compounded effect of forward speed and plowing depth on the efficiency. As it can be seen in the contour plots, simultaneous augmentation of forward speed in range of 2-6 km/h along with plowing depth in range of 10-30 cm led to integrated augmentation of the efficiency from the lowest zone (< 8%) to the highest zone (> 32%). These prognostication and interpretation obtained from the modeling results uncovered excellent agreement with those obtained from statistical analysis of the individual and compounded effects of forward speed and plowing depth on the efficiency (Section 3. 3).

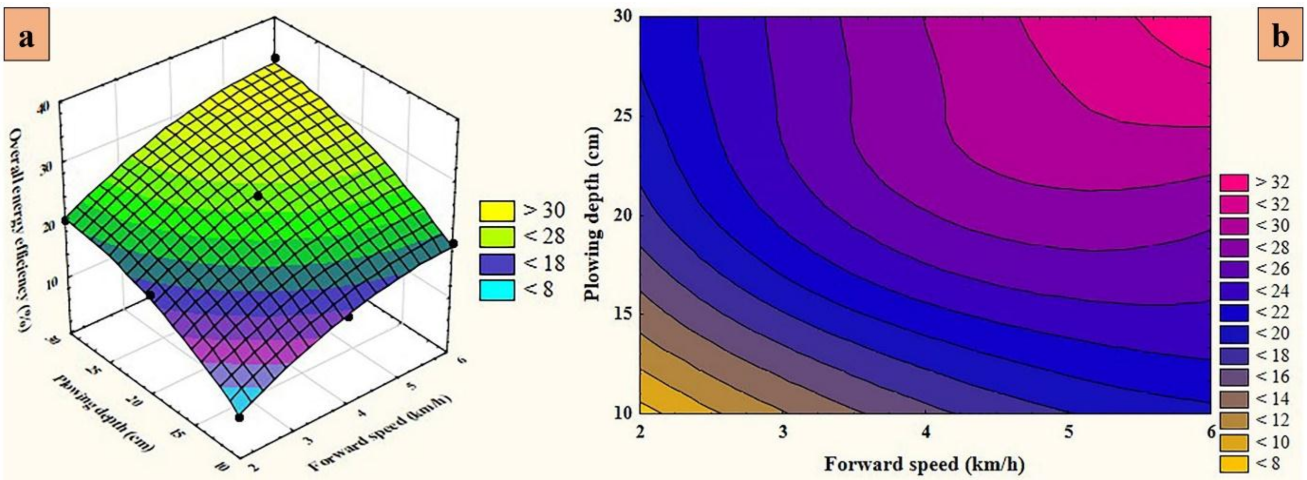

Figure 9 Prognostication of overall energy efficiency of the machinery in plowing process by the quadratic model with respect to simultaneous changes of plowing depth and forward speed, a) surface plot, and b) contour plot

4 Conclusion and recommendations

Key research findings for overall energy efficiency of the machinery in plowing process as influenced by the operational variables can be summarized as follows:

The compounded effect of forward speed and plowing depth on the efficiency was 4 and 3.2 times greater than that of the individual effect of forward speed and plowing depth, respectively. It was also found that the individual effect of plowing depth on the efficiency was more predominant (1.2 times) than that of forward speed.

According to the statistical indices of coefficient of determination (0.997), root mean square error (0.634%), mean relative deviation modulus (2.795%), and mean of absolute values of modeling residual errors (0.546%), the efficiency was more satisfactorily prognosticated by two-variable quadratic model than two-variable linear model. The model can be employed for direct prognostication of the efficiency without need for actual measurement of tractor performance parameters.

Physical perception obtained from the modeling results utilizing two-variable quadratic model indicated that simultaneous increase of forward speed from 2 to 6 km/h along with plowing depth increment from 10 to 30 cm led to nonlinear augmentation of the efficiency from 7.31 to 33.05%.

The aforementioned remarkable findings are prominent for associated agricultural managers, especially Iranian ones, who work in various realms of Agricultural and Biosystems Engineering included but not limited, fuel and energy management, and implement design. Ultimately, it is recommended to generalize analytical information and modeling results in future works for other soil textures and implement types in order to complement the knowledge in this realm.

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