

The Optimum Design Parameters in Terms of Total Specific Energy Requirements for the Rotary Blade Power Tiller under Unsaturated Sandy Clay Loam Soil Condition

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ABSTRACT

A mathematical modeling approach was applied to predict optimum design parameters in terms of the total specific energy requirements of a “Pick”, a “C”, an “I”, an “L” and a “J”-shaped rotary blades. The modified total specific energy requirement model mainly has been included, the forward speed of the machine, the rotational speed, the depth of soil cut, the width of soil cut, the rotor radius, the angle of periphery, the angle of rotation, the specific soil resistance, the dry soil bulk density and volume of soil tilled. At the same working conditions the total specific energy requirement was predicted to be 231.61, 160.72, 196.87, 168.56 and 167.56 kJ / m^3 for the “Pick”, the “C”, the “I”, the “L” and the “J”- shaped rotary blades, respectively. The highest specific energy requirement was exhibited by the “Pick”- shaped and the lowest by the “C”- shaped blade. The higher total specific energy requirement the lower volume of soil tilled and the most effective and optimum soil tillage operational cost is achieved. Compared to another study at the same soil condition the specific energy requirement per volume of soil tilled by the “Pick”- shaped blade was exhibited 1900 kJ / m^3 which was higher by 87.81 % than the “Pick”- shaped blade in the present study. Therefore, the model suggests rotary tiller development under local conditions.

Key words: power requirement, specific energy, rotary blades, sandy clay loam

INTRODUCTION

Energy requirement is the issue of concern in agricultural machinery management in crop production systems. The design characteristics of rotary blades are the biggest determinants of power consumption, so tillers requirement processors other tillage implements. The pushing power exerted by the operator behind the power tiller, the cutting and loosening of the soil slice, the overcoming of soil-metal friction

between the soil and the knife of the rotary blades and the throwing of the cut soil slice by the centrifugal action of the rotary blade are the total power requirements in the present study. The measurement of the total power required has been expressed in terms of total specific energy required per unit volume of soil tilled. Optimizing the total specific energy requirement is one the performance efficiency and the selection of criteria for land preparation implements. An optimization technique through the total specific energy

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requirement of various rotary blades of power tiller is conducted in this study.

Many studies have been reported regarding power and specific work requirements of rotary tillers in different soil field conditions. Dalin and Pavlov (1950) have developed a theoretical equation to predict power requirement for the determination of individual constituents, such as cutting, and loosening, throwing soil, power losses in power train, power for overcoming resistance to forward motion and pushing power requirement. Zhuk (1952), Sohne and Eggenmuller (1959) developed a mathematical model to predict the specific work of rotary cultivators. Sakai (1969) and, Hendrick and Gill (1971) developed a mathematical model to predict power requirement, and Sakai (1969) reported per meter working width in both sand and clay soil conditions. Bernacki *et al.* (1972), Perdok and Burema (1977) and Sineokov (1977) developed a mathematical model to predict the specific work for the efficiency of rotary cultivators in heavy and pure clay. Sineokov (1977) formulated the total power requirements of a rotary tiller model to determine for the operation of rotary cultivators. Gupta and Visvanathan (1993) formulated and developed the total power requirements of a rotary tiller model under saturated soil condition.

However, this study was aimed to fulfill the application of optimization theory for the design parameters in terms of the total specific energy requirements for rotary blade power tiller under unsaturated sandy clay loam.

MATERIALS AND METHODS

Configuration of rotary blades

Different configurations of rotary blades were used in the study. The used configuration and design parameters are shown in Figure 1 and Table 1.

Design parameters of various rotary blades and dry bulk density used in the study are presented in Tables 1 and 2.

Model selection criteria

Model selection was determined based on the facts of rotary tiller power requirements studies in different periods, soil types and conditions.

Dalin and Pavlov (1950) presented a general theoretical equation of rotary tiller to predict total power requirement as:

$$P_{Total} = P_{Cut} + P_{Throw} + P_{Loss} + P_{mf} + P_{Push}$$

Where

$$P_{Total} = \text{Total power requirement, kW,}$$

$$P_{Cut} = \text{cutting power requirement,}$$

kW,

P_{Throw} = throwing power the cut soil slice power requirement, kW,

P_{Loss} = Power loss in the power train, kW,

P_{mf} = overcoming soil-metal friction power requirement, kW,

P_{Push} = pushing power requirement, kW.

This model is defined but is not validated in terms of total specific energy requirement. Sohne and Eggenmuller (1959) used a general specific energy model for evaluating the efficiency of rotary cultivator and other cultivating tools,

$$E_W = \frac{E_E}{V_{ST}}. \text{ Bernacki } et al. (1972) \text{ formulated}$$

specific work under the description of torque per unit volume of soil tilled,

$$E_{SW} = \frac{2_p F_T}{Z L_d B_W L_B} + \frac{0.1 R_X}{B_W}. \text{ Both models,}$$

however, are undefined in terms of total specific energy requirement. Similarly, Sineokov (1977) formulated total power requirement of rotary cultivator as $P_{Total} = P_{cut} + P_{KE} + (1-\eta)(P_{cut} + P_{KE})$

$$+ \frac{V_f}{75} (\mu Q_z - R_x), \text{ in the model, the pushing, the over}$$

coming soil-metal friction power requirement and the volume of soil tilled were excluded. Saraswat (1987), under lateritic unsaturated sandy clay loam in soil bin laboratory, evaluated the performance

efficiency of “Pick”-shaped rotary blade in terms of specific energy requirement, pushing and rotary power requirement per unit of volume of soil tilled

as $E_{SP} = \frac{P_{Push} + P_{Rotary}}{V_{ST}}$. However, the cutting and the soil-metal friction were not described

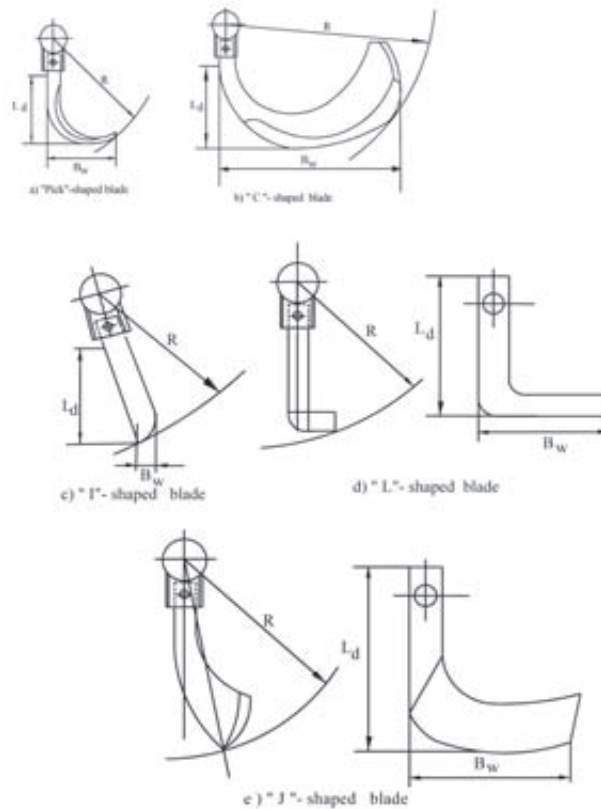


Figure 1 Type of rotary blade.

R , rotor radius, L_d , depth of soil cut, B_w , width of soil cut

Source: - 1. “Pick”- shaped (Saraswat, 1987)

2. “I”, “C” and “L”-shaped (Yatsuk et al., 1971; Beeny and Khoo, 1970; Sakai, 2000)

3. “J”-shaped (Kataoka and Shibusawa, 2002)

Table 1 Design parameters of various rotary blades.

Types of rotary blade	Rotational velocity (N) rpm	Rotor radius (R) m	Depth of soil cut (L_d) m	Width of soil cut (B_w) m
“Pick”-shaped	150 to 300	0.170 to 0.220	0.050 to 0.100	0.010 to 0.022
“C”-shaped	150 to 300	0.245 to 0.250	0.050 to 0.150	0.035 to 0.045
“I”-shaped	150 to 300	0.200 to 0.225	0.050 to 0.150	0.035 to 0.065
“L”-shaped	150 to 300	0.235 to 0.260	0.050 to 0.150	0.045 to 0.080
“J”-shaped	150 to 300	0.235 to 0.250	0.050 to 0.240	0.040 to 0.060

Source: - 1. “Pick”- shaped (Saraswat, 1987)

2. “I”, “C” and “L”-shaped (Yatsuk *et al.*, 1971; Beeny and Khoo, 1970; Sakai, 2000)

3. “J”-shaped (Kataoka and Shibusawa, 2002)

Table 2 Average minimum bulk densities of various soil textures.

Soil texture	Bulk density (g/cm ₃)
Coarse, medium and fine sand	1.80
Loamy and sandy clay loam	1.75
Loam and sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt and silt loam	1.55
Slity clay loam	1.50
Clay	1.40

Source: - James (1972)

For the present study the bulk density is 1.70 was selected.

significantly. Gupta and Visvanathan (1993) conducted experiments under saturated soil condition to predict power requirement of “L”-shaped rotary blades. The power requirement included cutting the soil (P_{cut}), throwing the cut soil slices by centrifugal action of the blade (P_{Throw}), over coming soil-metal friction (P_{mf}), soil-soil sliding friction (P_{sf}) as $P_{Total} = P_{cut} + P_{Throw} + P_{mf} + P_{sf}$ + idle power. In this model the pushing power and volume of soil tilled were excluded. Therefore, the model has not been governed in terms of total specific energy requirement. Theoretical model of Dalin and Pavlov (1950) is more describable among the above mentioned models which includes power requirements for cutting, throwing the cut soil slice, power loss, over coming soil-metal friction and pushing power. Therefore, this model was suitable for this study.

Model modification

The total specific energy requirement (power per unit volume of soil tilled) modification model is defined as a function of pushing (P_{Push}), cutting and loosening the soil slice (P_{cut}), over coming soil-metal-friction (P_{mf}) and throwing the cut soil slice (P_{Throw}) power requirement and volume of soil tilled (V_{ST}). The modified total specific energy requirement for the various rotary blades is exhibited as

$$E_{TSP} = \frac{P_{Push} + P_{Cut} + P_{mf} + P_{Throw}}{V_{ST}} \quad (1)$$

Hence, P_{Push} is pushing power requirement, kW, (Saraswat, 1987)

$$P_{Push} = R_x V_f \quad (2)$$

$$P_{Push} = \frac{7161.96(V_f P_e) \eta_C \eta_Z}{RN \cos(\varphi_1)} [\sin(\alpha) \cos(\varphi_1) + \cos(\alpha) \sin(\varphi_1)]$$

Where V_f is the machine forward velocity ($V_f = 0.20 - 30$ m / s; Sakai, 2000), P_e is the engine horse power of power tiller, ($P_e = 5.0$ to 12.16 hp; Mamansari, 1998), η_C is the power tiller efficiency ($\eta_C = 0.9$; Bernacki, *et al.*, 1972), η_Z is coefficient including a reverse of power tiller power ($\eta_Z = 0.75$; Bernacki, *et al.*, 1972); R is the rotor radius (m), N is the rotational velocity (rpm), α is the angle of direction ($\alpha = 42^\circ$; Sineokov, 1977) and (Sineokov, 1977) and φ_1 is the angle of periphery, ($\varphi_1 = 150$; Sineokov, 1977).

$$P_{Cut} = K_{SP} B_W L_d V_f \quad (\text{Dalin and Pavlov, 1950}) \quad (3)$$

P_{Cut} is the cutting power requirement, K_{SP} is specific soil resistance

resistance ($K_{SP} = 7000$ kg/m² for firm soil; Bernacki, *et al.*, 1972),

B_W width of soil cut, and L_d is depth of soil cut (m).

$$P_{mf} = L_d R V_f B_W S_{PW} \mu_K \quad (\text{Gupta and Visvanathan, 1993}) \quad (4)$$

P_{mf} is the over coming soil-metal friction torque requirement (k_W), S_{PW} is the dry soil bulk density ($S_{PW} = 1700$ kg/m³), and μ_K is the kinetic coefficient of soil-metal friction. The kinetic

coefficient of soil –metal friction occurs between the uncut soil and the metal surface under any soil condition by soil amendment implements. Besides, the value of the kinetic coefficient of soil –metal friction was calculated using the following equation as: (Gupta and Visvanathan, 1993)

$$\mu_K = \frac{1.09}{\sqrt{0.105RN}} \cdot$$

$$P_{Throw} = \frac{0.219RNL_dV_fB_WS_{PW}(3R - L_d)}{GZ} \quad (5)$$

P_{Throw} is the throwing the cut soil slice torque requirement (kW), Z is the number of blades on the drum, and G is the acceleration due to gravity. The total specific energy requirement (E_{TSP}) used for the various rotary blades was modified from Eqn (1) and it's derivation, Eqn (2) to Eqn (5), is written as the following:

$$E_{TST} = \left\{ \left(\frac{4834.323(V_fP_e)\sin(\alpha + \varphi_1)}{RN\cos(\varphi_1)} \right) + B_WL_dS_{PW} \right. \\ \left. \left(\frac{K_{SP}}{S_{PW}} + \frac{1.09R}{\sqrt{0.0105RN}} + \frac{0.219RN(3R - L_d)}{G} \right) \right\} / V_{ST}$$

Where V_{ST} is the volume of soil tilled per second, $10^{-6}m^3$. V_{ST} was calculated using the equation cited by Bernacki *et al.* (1972); $V_{ST} = B_WL_dV_f$.

Mathematical model optimization

Objective function

$$Min E_{TST} = \left\{ \left(\frac{4834.323(V_fP_e)\sin(\alpha + \varphi_1)}{RN\cos(\varphi_1)} \right) + B_WL_dS_{PW} \right. \\ \left. \left(\frac{K_{SP}}{S_{PW}} + \frac{1.09R}{\sqrt{0.0105RN}} + \frac{0.219RN(3R - L_d)}{G} \right) \right\} / V_{ST}$$

Subject to inequality constraints:

$$0.20 \leq V_f \leq 0.30, 5.0 \leq P_e \leq 12.16, 35^\circ \leq \alpha \leq 42^\circ, 10^\circ < \varphi_1 < 15^\circ, 150 \leq N \leq 300, S_{PW} = 1700, 5000 \leq K_{SP} < 7000, G = 9.81m/s^2,$$

For the "Pick"-shaped rotary blade

$$0.17 \leq R \leq 0.220, 0.01 \leq B_W \leq 0.022, 0.050 \leq L_d \leq 0.100,$$

For the "C"-shaped rotary blade

$$0.245 \leq R \leq 0.250, 0.035 \leq B_W \leq 0.045, 0.050 \leq L_d \leq 0.150,$$

For the "I"-shaped rotary blade

$$0.200 \leq R \leq 0.225, 0.035 \leq B_W \leq 0.065, 0.050 \leq L_d \leq 0.150,$$

For the "L"-shaped rotary blade

$$0.235 \leq R \leq 0.260, 0.045 \leq B_W \leq 0.080, 0.050 \leq L_d \leq 0.150,$$

For the "J"-shaped rotary blade

$$0.235 \leq R \leq 0.250, 0.040 \leq B_W \leq 0.060, 0.050 \leq L_d \leq 0.240,$$

Data were analyzed using the Lingo (2006) version 10 to optimize the design parameters with corresponding total energy requirements.

RESULTS AND DISCUSSION

Optimal solutions of design parameters with corresponding total specific energy requirement of individual rotary blade are presented in Table 3. From the results, at the same working conditions the total specific energy requirement was found to be 231.61, 160.72, 196.87, 168.56 and 167.56 for the "Pick", the "C", the "I", the "L" and the "J"- shaped rotary blades, respectively. The highest specific energy requirement was exhibited by the "Pick"- shaped blade and the lowest by the "C"- shaped blade. The higher total specific energy requirement the lower volume of soil tilled and the most effective and optimum soil tillage operational cost was achieved.

Compared to another study at the same soil condition, the specific energy requirement per volume of soil tilled by the "Pick"- shaped blade was exhibited $1900 \text{ kJ} / m^3$ (Saraswat, 1987), which was higher by 87.81 % than the "Pick"-shaped blade in the present study.

On the other hand, Beeny and Greing (1965) reported that the lower values of specific

Table 3 Optimal solutions of design parameters with corresponding total specific energy requirement of individual rotary blades.

Type of rotary blade	V_f m/s	P_e hp	R m	B_W m	L_d m	N Nrpm	α^0	φ_1^0	S_{PW} Kg/m ³	K_{SP} Kg/m ²	V_{ST} 10 ⁻⁶ m ³	E_{TSP} kJ/m ³
"Pick"-shaped	0.20	5.00	0.17	0.010	0.100	150	37.65	10.05	1700	5000	200	231.61
"C"-shaped	0.20	5.00	0.245	0.035	0.150	150	37.65	10.05	1700	5000	1050	160.72
"I"-shaped	0.20	5.00	0.200	0.035	0.150	150	37.65	10.05	1700	5000	1050	196.87
"L"-shaped	0.20	5.00	0.235	0.045	0.150	150	37.65	10.05	1700	5000	1300	168.56
"J"-shaped	0.20	5.00	0.235	0.040	0.240	150	37.65	10.05	1700	5000	1900	167.56

work requirement with a small range of volume of soil worked per rotor blade cut and these volumes were dependant only on the combination of depth and bite length of the blade over the range of values measured.

CONCLUSION AND RECOMMENDATION

The highest specific energy requirement was exhibited by the "Pick"- shaped blade and lowest by the "C"- shaped. The higher specific energy requirement the lower volume of soil tilled and the most effective and optimum soil tillage operational cost is achieved. Hence, the "Pick"-shaped blade was predicted to be optimum in this study.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Ethiopian Agricultural Research Organization (EARO) for funding this study and wish to acknowledge staffs of Department of the Farm Mechanics, Kasetsart University, Thailand for their support during study preparation.

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