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Design, development and evaluation of twig shredder for waste management and resource utilization in apple orchards

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ABSTRACT

An apple twig shredder was developed to manage waste and produce substrates for shiitake mushroom cultivation, mulch, and potting medium for clonal propagation of apple rootstock. The machine was evaluated for power requirement, throughput capacity, shredding efficiency, and size of shredded material. The shredder was standardized at 2880 rpm rotational speed and 15-25 mm twig diameter for which power requirement, throughput capacity, shredding efficiency and size of shredded material was obtained as 1.06 kW, 28.24 kgh^{-1}, 82.50% and 0.735 mm, respectively. Operational cost of the machine was estimated as Rs 70.38 per hour and shredding as Rs 2.5 per kg.

Keywords: Apple pruned wood, waste management, apple twig substrate, shredding.

INTRODUCTION

Apple (*Mallus domestica* Borkh.) is a temperate fruit grown on an area of 4.62, 0.31, 0.16 Mha in the world, India and predominantly in Jammu and Kashmir respectively, with a significant growth (326%) in the area in state of Jammu and Kashmir (Bhat *et al.,* 5). The study states that average of 26 t ha^{-1} of pruned wood as solid waste is produced in Jammu and Kashmir (4.26 MTyear $^{-1}$) for which recycling is a major problem for local farmers as it has no key application but conversion to charcoal (resulting in air-pollution), which is used as a fuel in *kangri*, a traditional Kashmiri heating pot (Fig. 1).

The potential alternate use of apple pruned wood are mulch, potting medium for production of clonal rootstock and substrate for shiitake mushroom. Although shredders for various agricultural residues have been developed, yet no apple twig shredder has been fabricated for production of substrates for growing shiitake mushroom. The engineering aspects and cutting force required for shredding of twigs have not been taken into design consideration of existing shredders. Thus, regarding the existing technological gap., the machine design, development, and performance evaluation were carried out during 2022-23 in workshop of College of Agricultural Engineering and Technology (CoAET), Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Srinagar, Jammu and Kashmir, India.

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MATERIALS AND METHODS

The conceptual design (Fig. 2) of twig shredder was based on the functional requirements, design considerations and operational viability using AutoCAD software version 2022. The apple twig shredder comprised of feeding hopper, shredding unit, power transmission system, output unit and main frame. The circular saw blades were mounted on a mild steel (MS) solid shaft and 1,440 rpm motor was used to check at which rotational speed of shaft the apple twigs get shredded. Belt and pulley drive was used for power transmission from electric motor to shaft and shaft speeds were achieved by changing size of pulleys. The shredding of twigs started at cutter blade speed of 1,920 rpm. Thus, achieved speeds of 1,920, 2,880 and 3,840 rpm were set. The locally available 40-tooth circular saw blades (diameter = 110 mm, thickness = 2 mm, Length of cutting edge = 5 mm, Tooth height = 5 mm, mass 70 g) were suitable to produce twig saw dust (Fig. 3). The blades were mounted on shaft to make the shredding unit of machine.

A V-belt drive and 76.2 mm pulley was used for power transmission with desired size of motor pulley calculated as:

$$N_1 D_1 = N_2 D_2 \quad (1)$$

Where, N_1 = rpm of electric motor pulley (1440 rpm), D_1 = diameter of motor (driver) pulley, N_2 = desired speed of the machine(shaft) pulley and D_2 = diameter of machine pulley (76.2 mm)

The desired size of shredding shaft pulley was 101.6 mm to achieve 1920 rpm, (similarly for 2880 and 3840 rpm, D_1 =152.4, 203.2 mm, respectively). For open

Fig. 1. Process of charcoal production for *Kangri* from apple pruned wood in Kashmir valley.

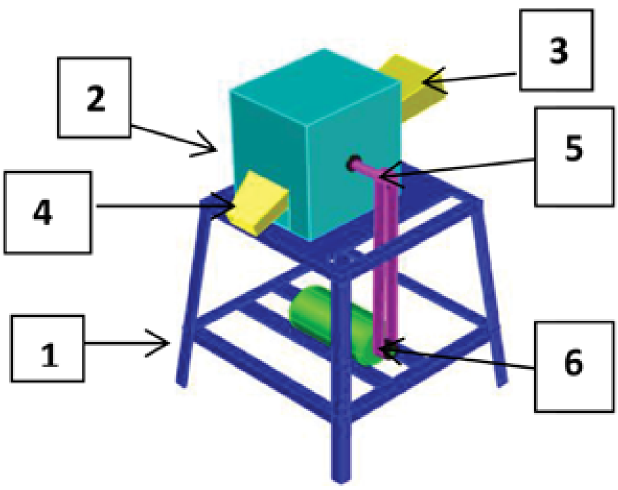

Fig. 2. Conceptual design of apple twig shredder.

1: Main frame, 2: Shredding unit, 3: Feeding hopper, 4: Output unit 5: Belt and pulley, and 6: Electric motor.

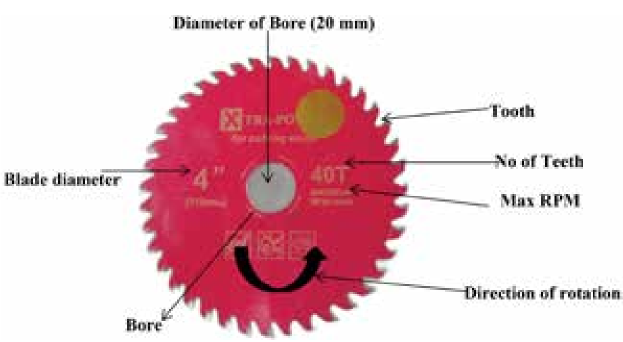

Fig. 3. Circular saw blade used in the apple shredder.

belt drive system, the length of belt was calculated by the formula given by Khurmi and Gupta (9).

$$L = \frac{\pi}{2}(D_2 + D_1) + 2c + \frac{(D_2 + D_1)^2}{4c} \qquad (2)$$

Where, L is length of belt required, mm, D_1 and D_2 is diameter of motor and machine shaft pulleys respectively in mm, C is centre to centre distance between the two pulleys in mm.

Thus, length of belt for 101.6 mm pulley =1357 mm. Similarly, for 152.4 mm, C= 590 mm and length= 1541 mm. Also, for 203.2 mm machine C=640 mm and length= 1725 mm. The angle of contact was calculated to check safety of belt and pulley. Angle of contact (ϴ) should be below 2.5 radians or there will be slippage between belt and pulley (Sharma and Agarwal, 15). ϴ (radians) was calculated by formula (Oladejo *et al.*, 12):

$$\Theta = (180 + 2\,\mathrm{Sin}^{-1}\ \frac{R_1 - R_2}{2c})\ \frac{\pi}{180} \qquad (3)$$

Where, R_1= radius of the driving pulley, mm, R_2 = radius of the driven pulley, mm, c = centre to centre distance from the pulley, mm

Therefore,

$$\Theta = (180 + 2\,\mathrm{Sin}^{-1}\ \frac{101.5 - 38.1}{2 \times 640})\ \frac{\pi}{180} = 2.24 \text{ radians}$$

Velocity of the belt was calculated by

$$V = \frac{\pi DN}{60} \qquad (4)$$

Where, D is the diameter (mm), N is rpm of pulley. Thus, velocity was found as 15.32 ms^{-1}.

The shaft was designed on the basis of power requirement for cutting of wood, given as;

$$P = F_cV \qquad (5)$$

Where, P = Power required (W), F_c = Main cutting force (N), V = Velocity of shaft (m/s) = 15.32 ms^1

For calculation of power (P) the cutting force (F_c) was calculated (Axelsson *et al.*, 3) as:

$$F_c = -7.37 + \delta_m\,(0.38d_8 - 224\alpha) + 15.61KH - 2.6KH^3 + 1.31r + 0.2V\,U\,(0.3KH - 0.01T) \qquad (6)$$

where δ_m is the average chip thickness in mm, d is the average density at 8% moisture content in kgm^{-3}, α is the rake angle in radians, KH is the grain angle in radians, r is the edge radius in μm, V is cutting speed, T is the temperature in °C, and U is the moisture content in %. δ_m was assumed as 0.579 mm, average density of apple wood ranges from 650-850 kgm^{-3} (Engineering Tool Box. 2004, 8), d_8 was assumed as 650 kgm^{-3}, α was measured and found as 30°, KH was found as 90 degrees as cutting in developed shredder corresponds to 90-90 cut (angle between direction of cutting edge and grain was 90° and angle between direction of movement of cutting tool and grain was 90°), r was assumed as 5 μm (Cristovao, 6). T was taken as 25°C as experiments were done at normal room temperature. U was calculated as 20% for dry apple wood and 55% for fresh wood on wet basis. For calculating power requirement, moisture content for dry wood was taken, as dry wood consumes more power for cutting. Cutting force was calculated as 96.68 N and power as 1481 W. The torque transmitted by the shaft was found as 3682 N.mm by the equation given by Khurmi and Gupta (9) as:

$$T = \frac{P \times 60}{2\pi N} \quad (7)$$

Where N is rpm of shaft

The equivalent twisting moment was given by Unuigbe *et al.* (18) as;

$$Te = \frac{\pi}{16} \times fs \times d^3 \quad (8)$$

Where,

f_s = Allowable shear stress of shaft, is usually taken as 42 Nmm^{-2} for suddenly applied loads (Sharma and Agarwal, 2007, 15) and d = diameter of shaft.

$$\text{Therefore, } d = \left(\frac{16 \times Te}{\pi \times FS}\right)^{1/3}$$

$$= \left(\frac{16 \times 3682}{\pi \times 42}\right)^{1/3}$$

d = 7.64 mm

Also, equivalent bending moment is given by Unuigbe *et al.* (18)

$$Me = \frac{1}{2}(M + Te)$$

Where,

M is Maximum bending moment

$$Me = \frac{1}{2}(M + Te)$$

Where,

W is weight on the shaft, kg, l is length of shaft (mm). Assumed value of l was taken as 396 mm. Weight on the shaft was calculated as

$$W = (M_t + M_p + M_s) \quad (11)$$

Where, M_t = Mass (kg) of twigs to be shredded in one batch during machine operation, M_p = Mass (kg) of pulley mounted on rotational shaft, M_s = Mass (kg) of saw blades on shaft.

$$M_t = \frac{m_p \times T_s}{T_t} \quad (12)$$

Where,

m_p = mass (kg) of material to be processed in 1 hour, T_s = Expected time (min) of shredding for one batch, T_t = Total time (min) required to process the expected quantity of the material.

In the experimental setup, it was found that 20 kg of apple twigs were shredded in one hour.

Capacity of shredder was assumed as 20 kgh^{-1}

Therefore, m_p = 20 kg, T_t = 1 h = 60 min

On the basis of experimentation, time of shredding (T_s) was assumed as 4.5 min

$$\text{Therefore, } M_t = \frac{20 \times 4.5}{60} = 1.5 \text{ kg}$$

Mass of pulley (M_p) was measured and was found as 1.5 kg. Mass of saw blades on shaft was calculated by

$$M_s = m_s \times n \quad (13)$$

Mass of saw blade (m_s) = 0.07 kg, number of saw blades used (n) = 100, M_s = 0.07 × 100 =7 kg and W = 1.5 + 1.5 + 7 = 10 kg

$$\text{Therefore, } M = \frac{10 \times 0.396^2}{8} = 0.1960 \text{ N.m} = 196 \text{ N.mm}, \; M_e = \tfrac{1}{2}(196 + 3682) = 1939 \text{ N.mm}$$

Equivalent twisting moment (M_e) was also given by Unuigbe *et al.* (18) as;

$$M_e = \frac{\pi}{32} \times f_b \times d^3 \quad (14)$$

Where f_b = maximum tensile or compressive stress and is usually taken as 56 Nmm^{-2} (Sharma and Agarwal, 15).

$$\text{Therefore, } d = \left(\frac{32 \times M_e}{\pi \times F_b}\right)^{1/3} = \left(\frac{32 \times 1939}{\pi \times 56}\right)^{1/3} = 7.06 \text{ mm}$$

Taking factor of safety as 2.5, diameter of shaft was set as 20 mm. From equation (5), power requirement was 1.481KW, thus a 2 hp, 1440 rpm AC motor was used. The hopper was designed for the largest diameter (≈35 mm) of twigs. Mass of twigs to be shredded in one batch (M_t) = 1.5 kg, average mass of a twig = 0.3 kg, total number of twigs to be shredded in one batch = 5, circular area of the twig = π × = 962 mm^2, Therefore, area of cutting throat = 4810 mm^2. Assumed height of throat = 24 mm. Thus, cutting width of throat = 200 mm

A trapezoidal hopper with top base, 360 × 260 mm and bottom base 240× 200 mm with height of hopper from top to bottom base as 126 mm following a smaller output unit (60º slope for the repose 52° were designed.

Performance Evaluation

The evaluation of machine was done in Workshop of College of Agricultural Engineering and Technology, SKUAST-K, Shalimar, Srinagar in year 2022. The raw material was collected from fruit research farm Shalimar campus, during pruning of apple trees. The material was kept for some time until its moisture content reached to 20%.

Two independent parameters which were taken for evaluating the performance of machine were twig diameter and rotational speeds of shredding shaft. The experiments were done in three replications. The diameter of twigs was measured using digital Vernier calipers. The twigs were then divided into diameters

Table 1: Independent and dependent parameters with their levels

Independent parameter	Level	Nomenclature (Value)	Dependent variables
Shredding shaft rpm	3	N_1, N_2 and N_3 (1920, 2880 and 3840)	Power requirement, Throughput capacity,
Diameter of twigs (mm)	3	D_1, D_2 and D_3 (5-15, 15-25 and 25-35)	Shredding efficiency, Size of shredded material

of 5-15, 15-25 and 25-35 mm. The mass of the material was measured using weighing balance. Three rotational speeds of the machine shaft were achieved using three different sized pulleys on the motor shaft. The three pulleys used were 101.6, 152.4 and 203.2 mm, which produced required speeds of 1920, 2850 and 3840 rpm, respectively. The independent and response parameters are given in Table 1.

Power requirement is expressed as the power consumed by the shredder during the operation and was measured by (Zaykov *et al.*, 19)

$$P_r = V\, I\, \eta \cos\varphi$$

Where, P_r = Power requirement, watt (W), V = voltage in the circuit, volts (V), I = current taken by machine, ampere (A), η = motor efficiency (75 %), cosφ = power factor of motor (0.83), current and voltage were measured by clamp meter.

Throughput capacity was measured as (Shahid *et al.*, 14):

$$\text{Throughput Capacity} = \frac{W_1}{T} \times 100$$

Where, W_1 = Weight (kg) twigs fed for shredding, T= Time (h) taken for shredding.

The shredding efficiency (η) was determined as (Ayo *et al.,* 4):

$$\eta = \frac{W_s}{W_t}$$

Where, Ws = Mass (kg) of shredded material, Wt = Mass (kg) of twigs to be shredded.

The size of the shredded material was evaluated using mechanical sieve analysis method (Mehta *et al.*, 11). A horizontal vibrating sieve shaker comprising of five sieves (IS 460-195, diameter of 18 and a bottom pan was used for sieve analysis. The opening sizes of the standard calibrated sieves were 2, 1.7, 1.4, 1 mm and 500 μ (run time 5 min.). Then weights obtained were used to determine mean mass diameter or MMD of material (Table 2).

$$MMD = \frac{1}{W}(0.125A + 0.375B + 0.75C + 1.2D + 1.7E + XF)$$

Where MMD is Mean mass diameter (mm), W is total weight of twig powder (A+B+C+D+E+F), X is mean of the measured diameter of the particles retained on the largest aperture sieve.

The brief description and working view of the developed apple twig shredder is shown in Table 3 and Fig. 4.

Table 2: Method for calculating mean mass diameter of twig powder.

Size of sieve (mm)	Dia. of particles passing the upper sieve and retained on the next small aperture sieve (mm)	Representative dia. of particles (mm)	Weight of twig powder (kg)
0.25	<0.25	0.125	A
0.5	0.25-0.5	0.375	B
1	0.5-1	0.75	C
1.4	1-1.4	1.2	D
2	1.4-2	1.7	E
>2		X	F

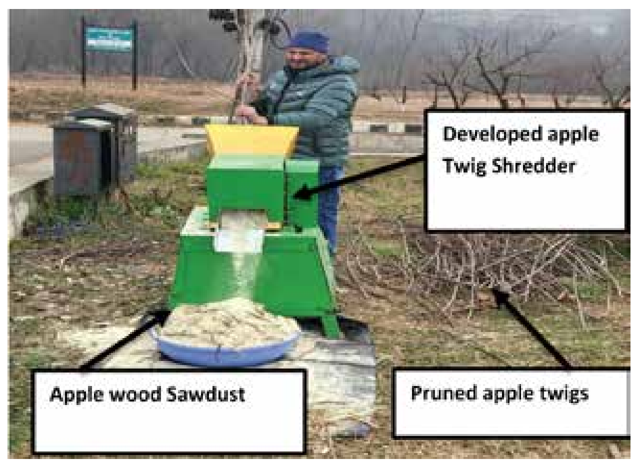

Fig. 4. Working view of the developed apple twig shredder at a high density apple farm.

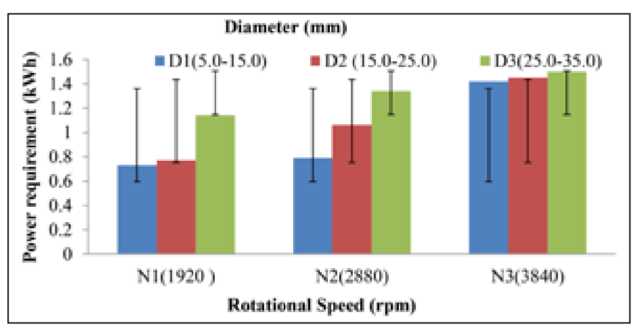

Fig. 5. Effect of rotational speed and diameter on power requirement of the apple twig shredder.

Table 3: Brief description of the developed apple twig shredder.

Sl. No.	Particulars	Specifications	Material
1	Feeding hopper		
	Shape	Trapezoidal	18 guage MS sheet
	Top base	360 ×260 mm	
	Bottom base	240 ×200 mm	
	Height	126 mm	
2	Shredding Unit		
	Shaft diameter	20 mm	Shaft = MS solid Casing = 10 guage MS sheet Conveying tray = 18-gauge MS sheet
	No of cutter blades	100	
	No of bearings	2	
	Shape of casing	Rectangular	
	Size of casing	300 × 250 × 340 mm	
	Shape of conveying tray	Rectangular	
	Size of conveying tray	300 × 203 mm	
	Cutting width	200 mm	
4	Power Source and Power Transmission system	2 hp (1.49 kW) single phase motor Rated rpm = 1440 Belt (B61) Pulley (154.2 mm, 76 mm)	
5	Output unit		18-gauge MS sheet
	Shape	Trapezoidal	
	Top base	150 × 80 mm	
	Bottom base	85 × 55 mm	
	Height	308 mm	
6	Main Frame		18-gauge MS sheet (50 × 50 × 5 mm) Angle iron
	Shape	Trapezoidal	
	Top base	460 × 460 mm	
	Bottom base	560 × 560 mm	
	Height	600 mm	
7	Total weight of machine	75.5 kg	

The statistical analysis of data was done using completely randomized design using OPSTAT Software.

RESULTS AND DISCUSSION

Power requirement (Fig. 5) increased with increase in diameter of twigs and rotational speed of shaft as cutting depth, wood density, plant fiber and feed per blade increases. The increase in power requirement is due to increased speed and torque required for the shaft, the above results are in agreement with (El-Hanfy and Shalby, 7).

Throughput capacity (Fig. 6) increased with increase in diameter of twigs and rotational speed of shaft as feeding of large diameter twigs is smoothly done into machine without any time wastage due to compactness and stiffness of twigs and with increased rotational speed of shaft lesser time is required to shred the twigs.

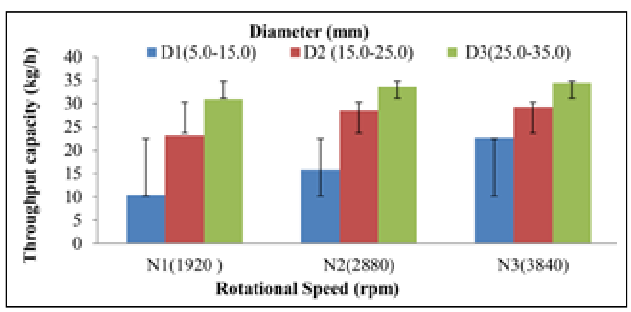

Fig. 6. Effect of rotational speed and diameter on throughput capacity of apple twig shredder.

Shredding efficiency (Fig. 7) increased with increase in diameter of twigs and rotational speed of shredding shaft as there is easy feeding of larger diameter twigs due to less flexibility and no choking, resulting in maximum shredded material and with increased rotational speed of shaft kinetic energy increases.

The size of shredded material was found to be inversely proportional to twig diameter and rotational speed of shredding shaft (Fig. 8) as increased speed and kinetic energy increases number of cuts per unit time. The decrease in size of shredded material with increase in diameter of twigs can be due to compactness and smooth feeding in larger diameter twigs as compared to smaller diameter twigs. The twig diameter (D) and shaft speed (N) on all the response parameters had significant effect at 5% level of significance. The first order interaction between twig diameter and shaft rotational speed (D×N) was also found to be significant for power requirement, throughput capacity and size of shredded material at 5% level of significance.

Design Expert software revealed that 15-25 mm diameter and 2880 rpm rotational speed resulted in power requirement of 1.06 kW, throughput capacity of 28.24 kg h^{-1}, shredding efficiency of 82.50% and 0.735 mm as size of shredded material. The developed cost-effective apple twig shredder may be efficient machine for converting apple twigs (a byproduct) into a valuable product (twig powder) as a suitable substrate material for shiitake mushroom cultivation, as mulch in horticultural crops and as a medium for clonal propagation of rootstocks in apple planting material production system.

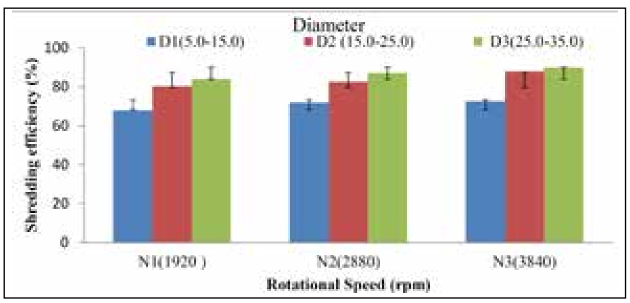

Fig. 7. Effect of rotational speed and diameter on shredding efficiency of shredder.

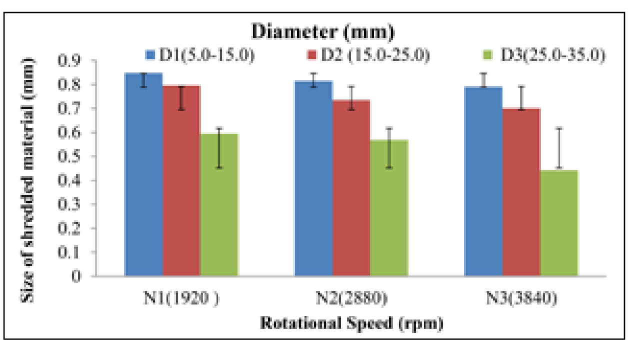

Fig. 8. Effect of rotational speed and diameter on size of shredded material.

AUTHORS' CONTRIBUTION

Conceptualization and designing of the research work (MA, TA); Execution of the experiments (TA, MA, HAP); and analysis (TA, MA, SR, SF, KK and MM); Preparation of manuscript (TA, MA, HAP).

DECLARATION

The authors have expressed that there exists no competing interest.

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