Comparison of the technical and economic performances of two different shredders on pomegranate pruning residues

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Abstract

Aim of study: The study aimed to examine the technical and economic performances of two different shredders for three windrow densities of pomegranate residues.

Area of study: The study was conducted in the Serik District of Antalya Province, Turkey.

Material and methods: Two different pruning residue shredders driven by tractor power take off (PTO) were used. Machine-I has pickup, shredding, screen units. Machine-II only has a shredding unit. The experiment was conducted at windrow densities of 1.49, 2.10, and 2.41 kg/m² in a pomegranate orchard; the study used a completely randomized split-plot design with two treatments and three replications.

Main results: The power values for the increasing windrow densities were 8.00, 11.73, and 18.47 kW/m for Machine-I and 5.08, 5.68, and 6.48 kW/m for Machine-II. Moreover, the average particle length of 68.6 mm shredded by Machine-I was approximately 20 mm smaller than that of Machine-II. The minimum unit energy value of Machine-II was 2.53 kWh/t at the maximum windrow density of 2.41 kg/m². This value for Machine-I was 5.58 kWh/t at the medium windrow density of 2.10 kg/m². The lowest unit cost for Machine-I and Machine-II was calculated as 27.2-7.1 US$/t (at medium density) and 16.8-3.5 US$/t (at maximum density), respectively.

Research highlights: The appropriate windrow densities for Machine-I and Machine-II were different in terms of energy requirements and total unit cost. Machine-I is more effective at consistently chopping the residues than Machine-II, but it requires more energy and a higher unit cost.

Additional key words: chopping; power and energy; particle length; machinery costs; Punica granatum.

Abbreviations used: PTO (power take off). Nomenclature: C₆ (annual average depreciation, US$/year); C₇ (fuel cost, US$/h); Ci (cost of interest, US$/year); Cₘ (cost of repair and maintenance, US$/h); FC (specific fuel consumption, L/kWh); f (number of parts in each group -the frequency, unit); f (number of parts, unit); h (accumulated use of machine, h); i (reel interest rate, decimal); LR (load ratio of tractor during the working, decimal); N (economic life of the machine, year); P (purchase price, US$); Pₚ (price of fuel, US$/L); P₁ (tractor power, kW); RF₁-RF₂ (repair and maintenance factors, decimal); S (salvage value, US$); Xₐ (average particle sizes, mm); Xₐi (group’s particle sizes, ... mm)

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Introduction

Fruit production has an important place in among the agricultural cultivation branches. Unlike other agricultural crops, fruit trees, are perennial plants, and they should be pruned either every year or within a few years to increase the quality and quantity of production. Subsequently, a residual woody biomass is obtained depending on the tree’s properties such as its structure and pruning frequency. These agricultural operations require disposing of the residues; otherwise, they become an obstacle to the other cultivation processes.
The residues should be evaluated based on different properties, such as farm sizes, cultivation methods, regional characteristics, technology usage, costs etc. Residues can be used as mulch on the ground or mixed into soil. They are also utilized as raw materials for power and industrial plants (Ntalos & Grigoriou, 2002; Velázquez-Martí et al., 2011; Fedrizzi et al.; 2012, Spinelli et al., 2012, Velázquez-Martí et al., 2012; Fernandez-Sarria et al., 2019). Regardless of the method that is used, the size of the residue has to be reduced by shredding it. For mulching purposes the shredded residues can either be recycled on site, or removed from the orchards and then transported to processing plants (Spinelli & Picchi, 2010; Velázquez-Martí et al., 2011). Some studies have pointed out that the pruned residues are collected and baled without reducing their size and they are then transported to power and industrial plants before being shredded (Savoie et al., 2008; Spinelli et al., 2010, 2014). Usage of the pruned residue as biomass for energy production, in boilers or as raw material in some industrial plants requires specific processes or technologies. For this purpose, many studies focusing on different pruning residues have been conducted in different countries. Currently, many machines have been designed (Recchia et al., 2009; Damour & Lavoie, 2010; Fedrizzi et al., 2012; Spinelli et al., 2014; Manzone, 2016), different machines and technologies have been compared in terms of management (Savoie et al., 2008; Spinelli et al., 2010; Do Canto et al., 2011) and some logistics model have been developed (Spinelli & Magagnotti, 2010; Ghaffariany et al., 2013; Magagnotti et al., 2013). These studies primarily concentrated on woody residues especially in Mediterranean countries.

Spreading residues into the soil or mulching them could be a good solution, especially for regions that do not have technological infrastructures for energy production and a market for woody residues, or those that do not have enough organic matter in their soil. These two applications could be defined as being more practical and simpler than the other methods. Shredded pruning residues increase the organic matter content, which improves some of the physical and chemical characteristics of soil, such as its water holding capacity, humic content, nutrient adsorption capacity, pH buffering capacity and microbial diversity (Holtz et al., 2005). Moreover, the residues are used to protect the soil from erosion; thus, these applications are becoming a common practice in sustainable agriculture (Calatrava & Franco, 2011; Jimenez et al., 2013; Manzanares et al., 2017). Therefore, many farmers in different countries prefer the aforementioned techniques. Calatrava & Franco (2011) pointed out that the use of pruning residues as mulch has been adopted by 43% of the surveyed farmers in the olive orchards of a southern province in Spain. Çanakcı (2014) stated that since the 2000’s utilization of the residues on-site, instead of burning, has begun to increase in Turkey, which has a total fruit orchard area of more than 3.3 million ha that is increasing every year (Turkish Statistical Institute, www.tuik.gov.tr). Adamchuk et al. (2016) stated that these applications are required to reduce energy and labor consumption, but and to lower of the demand for mineral fertilizers, which will significantly improve the ecological indices of the natural environment in Russia, Ukraine and Armenia.

Some studies focused on different pruning residues in different countries. Holtz et al. (2005) investigated the effect of almond pruning residues on soil and petiole nutrients, soil aggregation, water infiltration, and nematode and basidiomycete populations. Repullo et al. (2012) studied the capacity of different pruning residue applications on olive orchard lanes to increase carbon content. Yilmaz et al. (2017) examined the effects of the application of vine pruning residue on soil properties and productivity under Mediterranean climate conditions in Turkey. Significant developments were observed in terms of the organic matter content of soil and various plant macro nutrient elements, especially phosphorus and nitrogen.

For each pruned material utilization methods, the process should be done with appropriate machines, systems, or organizational planning in terms of work quality and costs. Studies related to the machines that use the remains as feedstock material in energy or industrial plants have been conducted in many countries. However, there are a limited number of studies on machines that are used to chop pruning residues to create mulching or provide organic matter to the soil. For instance, Çanakcı et al. (2010) aimed to determine basic management data of power take off (PTO) driven pruning residue shredder on different pruned residues obtained from grapes (vineyards), and pomegranate, and orange, and avocado orchards. Moreover Dereli & Çakır (2014) determined the cutting performance of different shredders used in vineyards for chopping after pruning. Adamchuk et al., (2016) stud-
ied how to increase the chopping and spreading of pruning residue to develop a new wood shedder design.

Today, although different shredders can be used, hanging or semi-hanging shredders driven by PTO are commonly manufactured and used in orchards in many countries. It is very important to know some of the parameters of the machines, such as the size of the shredded particle, the power requirements, the energy consumption per shredded mass, and the usage costs, and to compare the selection and usage stages of these machines in terms of work efficiency and biomass management. This management data is very useful for planners, consultants, designers, manufacturers and farmers. Thus, the present study aimed to compare and contrast the technical and economic performance of two different shredders driven by PTO in order to improve soil properties.

Material and methods

The PTO power, area and material capacity, unit energy, particle length and machinery cost values of two shredders were determined and compared in terms of their technical and economic performance. An orchard experiment was conducted to obtain basic operational parameters such as PTO torque, PTO revolution, forward speed and residue densities.

The main material of the study consists of two shredders, Machine-I and Machine-II manufactured in Turkey (Ersun Agricultural Machinery Company, Tekirdağ City) driven by tractor PTO. Both machines chopped the pruning residues, which were formed as a windrow, and left the residues on the soil surface.

Machine-I was a combined machine and it had pickup, shredding and screen units. The motion from the PTO to a gear box placed on the chassis was transmitted to the pick-up and shredding units using double-side output. A total of 18 fingers were placed in 4 rows on the rotor of the pick-up unit, which picks up the pruned residue materials from the windrow and transfers them to the shredding chamber. The basic parts of the shredding unit consist of a rotor and 18 flail blades placed in the rotor. The blade type, also called a universal blade, consists of three free parts, two L-shaped blades located opposite of each other and one straight blade in the middle. The blades are made of alloyed steel material of 30 Mn5 (DIN EN 10083 3: 3006) and the total weight of one blade group is 1730 g (Fig. 1a). The screen forms the lower part of the shredding chamber. A steel cover was placed on the chassis to constitute the upper part of the chamber. During the experiments, the screen unit with 36 mm holes was used. The experiment started with the brand new/unused blades on both machines. While operating the machine, the chopped materials passing through the holes were left on the soil surface. During the chopping operation, the machine was carried by a supporting rear tire. The second machine, Machine-II, only has a shredding unit (Fig. 1b). A cylindrical roller was placed at the rear of the machine instead of a supporting tire. Machine-II had 18 blades; the revolution of the blades was 1827 rev/min (in the PTO revolution, 540 rev/min), and the working width was 1.70 m. The total weight of the machines was 800 kg (Machine-I) and 530 kg (Machine-II).

The experiment took place in a 15-year-old pomegranate (Punica granatum cv. Hicaz) orchard located in the Serik District of Antalya Province in Turkey. The average thickness and the moisture values of the residues were measured as 17 mm and 28.5% wet basis (w.b.). In the orchard, the spacing within each row and between the rows was 4 × 4 m. The residues were shredded by passing each row once time. Hence, the machine working width of both machines was 4 m. Prior to the experiment, only one gear stage was found to be appropriate as the eligible operating speed; thus the pruning residues were chopped at one forward speed of 1.5 km/h. The machines could not be operated at higher speeds, because the time required for shredding was limited to the forward speed in the trial conditions. Generally, higher speeds, such as 1.8 km/h to 2.0 km/h, cause blockages, while lower speeds reduce the machine’s capacity. Both machines were driven by a New Holland TD 75 D tractor with a 55.2 kW engine power.

The experimental study was arranged in a completely randomized split-plot design with two treatments and three replications. The main treatments include two machines (Machine-I and Machine-II) and three windrow densities (1.49, 2.10 and 2.41 kg/m²) arranged in lengths of 30 m plots.

Before the experiment, regular windrows were formed manually. To determine the minimum density (D1), the amount of material that provides continuity on the windrow that is too little to cause interruption was considered. The maximum density (D3) was determined based on the machine’s density level. The other density (D2) is a value between the other specified quantities. The values of the average sizes were calculated from 10 different points. The average windrow width and high values were found to be 136-28 cm, 142-36 cm, and 155-42 cm for the D1, D2 and D3 windrow densities, respectively.

A measuring system was used to determine PTO torque, PTO power and rotational speed. It consists of a torque meter mounted to the PTO output (Datum Electronics Company, Series 420, Isle of Wight, UK)
findings reported in other similar studies (Çanakcı et al., 2010; Fedrizzi et al., 2012). The working width of both machines was taken as 4 m, since the shredders only passed in the middle of the two rows, once. The energy requirement per unit mass (kWh/t) was calculated by dividing the required power during the shredding operations by the material capacity values.

The particle lengths were considered to compare particle size distributions. Samples of the chopped material were collected from each of the plots. For this purpose, an iron frame (1×1 m) placed in each plot was used, then all of the remaining materials inside the frame were collected for analysis. A total of 11 frequencies with the unit of mm (˂30, 31-60, 61-90, 91-120, 121-150, 151-180, 181-210, 211-240, 241-270, 271-300, >300) were considered to determine the average particle length and to compare the two shredders. A digital caliper with an accuracy of 1% was used to measure the length of the shredded particles. The average particle size of the measured values was calculated using

Figure 1. Schematic views of Machine-I (a) and Machine-II (b).
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The running costs (variable costs) vary directly with the amount of usage; they consist of fuel, oil, repair maintenance and labor. The equation used to calculate the cost of fuel (Işık et al., 1988; Sayın & Özgüven, 1995) was:

\[ C_f = P_t \cdot LR \cdot FC_s \cdot P_f \]  \[4\]

where \( C_f \) is the fuel cost, US$/h; \( P_t \) is the tractor power, kW; \( LR \) is the load ratio of the tractor during the operation, decimal; \( FC_s \) is the specific fuel consumption, L/kWh; and \( P_f \) is the price of fuel, US$/L.

Oil cost was taken as 15% of the fuel cost (Evcim, 1990). The equation to calculate the repair and maintenance cost (ASABE, 2015) was:

\[ C_{rm} = \left( RF_1 \right) \cdot P \cdot \left( \frac{h}{1000} \right)^{RF_2} \]  \[5\]

where \( C_{rm} \) is the cost of repair and maintenance, US$/h; \( RF_1 \) and \( RF_2 \) are, respectively, the repair and maintenance factors, decimal; and \( h \) is the accumulated use of machine, h.

The labour cost and the other data used in the equations were calculated by considering the field experiment and Turkish market conditions.

Results and discussion
Power requirements, particle lengths and unit energy consumptions

The values of the average PTO powers per working machine width, shredded particle lengths and energy consumption per unit mass measured for both machines in the experiment are given in Table 1. The indicated average values determined for three different windrow densities are also shown in Table 1.

| Table 1. Average PTO power, particle lengths and energy consumption values of the machines and for different windrow densities |
|---------------------------------|---------------------------------|-----------------|-----------------|
| Machines                        | Average PTO power, kW/m         | Average particle length, mm | Average energy consumption per unit mass, kWh/t |
|---------------------------------|---------------------------------|-----------------|-----------------|
| Machine-I                       | 12.73 ± 1.92 a*                 | 68.58 ± 1.60 a  | 6.08 ± 0.31 a   |
| Machine-II                      | 5.75 ± 0.47 b                   | 87.74 ± 2.84 b  | 3.03 ± 0.31 b   |
| \( p \)                         | <0.001                          | <0.001          | <0.001          |
| Windrow density, kg/m²          |                                 |                 |                 |
| 1.49                            | 6.54 ± 0.79 a*                  | 77.97 ± 4.69    | 4.76 ± 0.54     |
| 2.10                            | 8.71 ± 1.39 b                   | 78.73 ± 4.90    | 4.20 ± 0.64     |
| 2.41                            | 12.47 ± 2.72 c                  | 79.28 ± 4.50    | 4.70 ± 0.99     |
| \( p \)                         | <0.001                          | 0.940           | 0.216           |

* Different letters within a column denote significant differences.
Both machines shredded the pruning residues collected from at distance of 4 m between two rows. Machine-I consumed more power (120%) than Machine-II. The power values between the two machines were significantly different ($p<0.001$). The average power was 5.75 kW/m for Machine-II; it was 12.73 kW/m for Machine-I. Machine-I requires more power due to its pick-up unit, screen unit, and shredding unit. Windrow densities have significant effects on the PTO power consumption ($p<0.001$). Increasing the windrow density from 1.49 to 2.41 kg/m$^2$ caused increases in the average power from 6.54 to 12.47 kW/m (Table 1). Moreover, it was concluded that the effect of machine × density interaction was significant for power consumption ($p<0.001$). The power requirements for the different residual densities are shown in Fig. 2.

As seen in Fig. 2 the power values increased from 8.00 to 18.47 kW/m in Machine-I; these values were lower and more stable (5.08-6.48 kW/m) in Machine-II. The variance analysis results showed that, while there were significant differences among the power values of Machine-I at different windrow densities ($p<0.001$), there was no significant difference among the power values of Machine-II. It can be said that the residual materials were picked up and shredded in a more controlled manner by the pick-up and sieving units on Machine-I. In Machine-I, the pruned residues, taken into the chopper chamber, must be disintegrated until they pass through the screen holes in order to be left on the soil surface. Thus, the shredding time increased with increasing windrow densities at the same working speed. Dropping the chopped material from the shredding chamber became more difficult as the windrow density increased; therefore more power was to complete the shredding operation. In the experiments, no clogging was seen. However, if the machine would have worked in higher windrow densities and with the same tractor speed, some clogging might have occurred.

The average lengths of the material chopped by Machine-I and Machine-II were 68.58 mm and 87.74 mm, respectively, which is a significant difference ($p<0.001$). In terms of particle mean values, there was a difference of about 20 mm between the two machines; Machine-I chopped the pruning residues into size that were about 25% smaller than Machine-II. The regular transfer of the residues from the windrow to the shredding chamber followed by chopping of the brush in a more controlled way caused smaller particle lengths in Machine-I. The average length values at three different windrow densities (Table 1) were 77.97, 78.73 and 79.28 mm for both machines; no significant difference was observed ($p=0.940$). We also found no machine × density interaction for particle lengths.

The length of the chopped material for each machine at different windrow densities are given in Fig. 3. Figure 4 shows some pictures of the chopped pruning residues for both machines at different windrow densities.

As seen in Fig. 3, the particle lengths ranged from 68.80 to 70.37 mm in Machine-I; these values were from 87.13 to 88.19 mm in Machine-II. Correct realization of the main processes such as picking the residues from the windrow, and chopping and spreading them to the soil surface, increases the work efficiency. The probability of achieving mentioned operations was higher in Machine-I, which has a pick-up unit and a screen unit, than Machine-II. The sizes and the distribution of the particles should be considered when comparing the two machines. The first average particle size can be more acceptable in terms of decomposing in the soil. For

![Figure 2. PTO power requirements per working machine width. The different upper and lower case letters above the histogram bars indicate significant differences ($p<0.001$, Duncan test) between the machines and the windrow densities, respectively.](image-url)
Comparison of the performances of two different shredders on pomegranate pruning residues

Machine-II, some problems such taking the residue material into the shredding unit and the irregular distribution of the particles to the soil surface, were seen during the trials (Fig. 4). A particle size of 1-3 inches (2.54-76.2 mm) was recommended to increase the surface area of the material that is to be composted and contacted with microbes (Goldstein & Diaz, 2010). The average values of Machine-II remained outside the upper limit of 76.2 mm. Moreover, these materials were not distributed homogeneously (Fig. 4). Since Machine-II collects residues by sweeping, regular residue feeding could not be observed; sometimes, this was because feeding the material into the shredder was prevented during the field experiments. In this case, it may be advisable to add a pick-up unit as seen in the machine developed by Adamchuk et al. (2016).

The unit energy consumption values were calculated as kWh/t. The field capacity for both machines was 0.51 ha/h ([1.5 km/h×4 m×0.85]/10). Considering the windrow densities and the field capacity value, the machine capacities used to determine energy consumption for unit mass were calculated as 1.50, 2.72 and 3.40 t/h, respectively.

Machine-I needed more power than Machine-II in terms of per unit shredded mass. The pick-up and screen units in Machine-I affected the energy consumption, similar to power values. The effects of the different machines on energy consumption per unit mass were...
between the average particle lengths for Machine-II was insignificant, it can be suggested that the D3 windrow density (2.41 kg/m$^2$) is more suitable for this machine due to the minimum unit energy consumption. Similarly, the appropriate windrow density for Machine-I was found for D2 windrow density (2.10 kg/m$^2$).

In comparison, Machine-I, which had same type of blades as Machine-II, has an advantage in terms of the ability to produce smaller chopped particles. However, although Machine-I does a better job of shredding the residues, it consumes more power. Most farmers prefer Machine-II due to its simple structure and lower costs. In this circumstance, some extra work may be needed for Machine-II to make it easier to take the residues to the shredding unit and obtain smaller and regular sized particles. Some studies aimed to decrease the power requirements and reduce the particle sizes of shredders that are similar to Machine-II (Dereli & Çakır, 2014; Adamchuk et al., 2016). However, studies are needed to investigate how to decrease power consumption for the shredders in Machine-I.

**Machinery costs**

The fixed and variable costs of the machines are shown in Table 2 and Table 3, respectively.

![Energy consumption values per unit of shredded residue. The different upper case letters above the histogram bars denote significant differences between the machines at $p<0.001$. The different lower case letters above the histogram bars denote significant differences between windrow densities ($p<0.05$).](image-url)
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It has a negative effect on to the total unit cost. Therefore, in terms of both energy requirements and total unit costs, the appropriate windrow densities for Machine-I and Machine-II were different. Machine-I is more effective at consistently chopping the biomass material than Machine-II, but it requires more energy and higher unit costs.

In conclusion, technical and economic performance data were obtained for two different residue shredders driven by tractor PTO while working with pruned pomegranate branches. Significant differences were found the performances of the machines. These data were determined under practical conditions, so they can be beneficial for farmers, contractors, researchers and manufacturers. To ensure better machine performances, studies needed to determine how to decrease power consumption for Machine-I and increase chopping efficiency of Machine-II.

The purchase price of the machines directly affects the fixed costs, and they are calculated annually. As seen in Table 2, these values were 686.6 US$/yr and 359.7 US$/yr for Machine-I and Machine-II, respectively. Annual costs can be converted into unit cost values by dividing these values into the yearly usage values such as hours and area.

The estimated life of these machines is determined as 2000 hours and 10 years (ASABE, 2015). If the machines were used for 200 h/yr, the hourly fixed costs can be defined as 3.4 US$/h and 1.8 US$/h for Machine-I and Machine-II, respectively. Increased use of machine within a year will reduce the fixed cost per hour or vice versa.

As expected, the variable costs were higher for Machine-I than Machine-II, the cost per usage time ($/h) increased with increasing windrow densities. The largest share of variable costs consisted of the fuel and oil costs. In terms of the unit of US$/t, the variable costs are expected to decrease as the windrow density increases (Table 3). These values decreased from 5.1 US$/t to 3.2 US$/t for Machine-II; for Machine-I, they first decreased from 7.2 US$/t (D1) to 6.2 US$/t (D2) and then increased to 7.0 US$/t (D3).

Total unit costs were calculated by considering the annual machine usage of 200 hours. These costs per hour increased based on the windrow densities; they ranged from 21.9 US$/h to 36.6 US$/h and 15.0 US$/h to 16.8 US$/h for Machine-I and Machine-II, respectively. The minimum total unit cost per shredded residual mass was 7.1 US$/t for the D2 windrow density (2.10 kg/m²) for Machine-I; it was 3.5 US$/t for the D3 windrow density (2.41 kg/m²) for Machine-II.

As noted in the unit energy consumption, excess pruning residue in the shredding chamber greatly increases the power requirement for Machine-I. This causes the highest energy consumption in the D3 and

Table 3. Machinery variable and total unit costs

| Machines | Windrow density, kg/m² | Fuel and oil | Repair and maintenance | Labour | Total variable cost | Total unit cost* |
|----------|------------------------|--------------|------------------------|--------|---------------------|-----------------|
|          | US$/h | US$/t | US$/h | US$/t | US$/h | US$/t | US$/h | US$/t | US$/h | US$/t |
| Machine-I | 1.49 | 12.3 | 4.8 | 2.0 | 0.8 | 4.1 | 1.6 | 18.4 | 7.2 | 21.9 | 8.5 |
|          | 2.10 | 17.6 | 4.6 | 2.0 | 0.5 | 4.1 | 1.1 | 23.7 | 6.2 | 27.2 | 7.1 |
|          | 2.41 | 27.1 | 5.7 | 2.0 | 0.4 | 4.1 | 0.9 | 33.2 | 7.0 | 36.6 | 7.7 |
| Machine-II | 1.49 | 8.0 | 3.1 | 1.1 | 0.4 | 4.1 | 1.6 | 13.2 | 5.1 | 15.0 | 5.8 |
|          | 2.10 | 8.9 | 2.3 | 1.1 | 0.3 | 4.1 | 1.1 | 14.1 | 3.7 | 15.8 | 4.2 |
|          | 2.41 | 9.9 | 2.1 | 1.1 | 0.2 | 4.1 | 0.9 | 15.1 | 3.2 | 16.8 | 3.5 |

*The annual usage of the machines was considered to be 200 h

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