Analysis and development of cost equations for mechanized agave transplantation versus manual

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Abstract

The agave crop (Tequilana weber) has gained economic importance in Mexico, leading to an increase in the cultivated area. Transplanting agave in field represents a significant cost due to labor expenses, which is also scarce. Hence, there is a convenience in mechanizing the process. In this study, equations are developed to compare the costs of manual transplantation versus mechanized transplantation, considering a prototype of a transplanting machine. To determine the equation for the cost of manual transplanting, an average payment per transplanted plant in the field and a traditional planting density were considered, resulting in a transplantation cost of US$ 385 per hectare. For the equation of mechanized transplantation cost, the following factors were involved: rental of an agricultural tractor, cost of the transplanting machine, and payment to three operators assisting the machine, resulting in a cost of US$ 326.2 per hectare. A decision criterion was established to compare manual and mechanized transplantation, where the latter represents 85% of the first, justifying its choice. It was found that the maximum value for the machine is US$ 39,000, in order to get a cheaper mechanized transplanting than manual one. However, considering an average lifespan of 1200 hours for agricultural planters, the maximum value should be US$ 22,500 to recover the investment within that time. The developed equations facilitate the determination of the cost of manual transplantation, the cost of mechanized transplantation, their comparison, and their use in determining the costs of agave transplantation activities.

Keywords: Pups. Prototype. transplanting machine.

1. Introduction

The agave is an endemic plant of Mexico that grows in different states of the country. Jalisco and Guanajuato are the main producers, according to the Federal Government's System of Agri-Food and Fisheries Information (SIAP), based on official production records up to the year 2021 (SIAP, 2023). The Tequila Regulatory Council (CRT) is the official dependence that determines the designation of origin (DOT) zone, where five states hold DOT: Jalisco, Guanajuato, Michoacán, Nayarit, and Tamaulipas (CRT, 2022). The regulation indicates that agave produced in this zone can be used in the production of the alcoholic beverage called tequila. All the municipalities within Jalisco are included in the DOT zone, but this is not the case for the other states. However, the agave plant is grown in 18 of the 32 states of Mexico and is used not only for tequila production but also in various products such as mezcal, honey, syrup, inulin, pellets, among others (Álvarez-Chávez et al., 2021; Macías and Valenzuela, 2009).

According to SIAP, in 2021, 139,314 hectares were planted throughout the country (SIAP, 2023). Considering the average population density of 3,500 plants per hectare, the approximate value of plants reached 487 million. Since the transplanting process is done manually, and a laborer can plant up to 800 plants per day, the amount of labor required to carry out this activity is close to 610,000 labor days. The transplanting season in Jalisco and neighboring states starts at the beginning of the year and ends at the beginning of summer, as rains make it difficult to access the areas where the cultivation is established. Therefore, there are an average of 6 months available as the maximum time to perform this activity. This requires adequate planning in terms of plant supply and the locations where the cultivation will be established, in addition to having the work crews of laborers who carry out the transplanting work. In some states of México, the available labor for agricultural activities is decreasing, making it challenging to find laborers. The payment and working conditions must be attractive to encourage laborers to continue working in agriculture and not shift to industries, which offer better comfort and benefits that the field does not provide (Herrera-Pérez et al., 2018). Tequila manufacturing companies, which establish their agave plots, have found that the payment per transplanted plant is what is most convenient, both for them and for the workers. The prevailing amount in the cultivation zones ranges from US$ 0.075 to 0.11 per plant. It is difficult to find workers willing to transplant agave for less than this value. Taking the highest payment value, transplanting one hectare of agave represents a labor cost of US$ 385, considering only the labor for the transplanting work itself, without including additional costs for transport and handling of the plants to the planting site (Díaz-Víquez et al., 2017). Additionally, with 5 people working at their maximum capacity (800 plants per day), they could transplant one hectare in a day. The traditional way is a group of 30 laborers that should be able to transplant up to 6 hectares per day, but this amount is reduced when considering downtime. The price of harvested agave can be considered as US$ 1 kg^{-1} (FIRA, 2022), covering the transplanting costs would not represent an immediate problem for those within the DOT zone, who receive a better price for agave when selling it. However, this is not the case for those outside the DOT zone, whose income is lower. For instance, the state of Michoacán receives only 53% of the value for its harvest compared to states within the DOT zone, as analyzed by the Agricultural and Fisheries Information System (SIAP, 2023). Hence, mechanizing the transplanting process to reduce these costs could be an alternative to improve income. In the same context, the scarcity of labor leads to considering the viability of mechanizing the transplanting process. This does not mean displacing labor and taking away job opportunities (Schmitz and Moss, 2015) but rather having available agricultural machinery to carry out tiring, repetitive, and monotonous activities, allowing workers to perform their tasks in better comfort or making them more productive (Negrete, 2011). In this study, equations are developed to determine the cost of mechanized transplantation, the cost of manual transplantation, and the time required to recover the investment made in a transplanting machine. These costs are analyzed and compared to determine how much it would cost to mechanize agave transplanting compared to maintaining the manual transplantation process as it is currently done (Hossen et al., 2018).

2. Literature Review

In a research study Aykaz et al. (2017) recommend the use of machines for vegetable transplantation instead of continuing to rely on manual labor in the traditional method. After conducting an economic analysis, they found that mechanical transplantation is more cost-effective. Additionally, the study demonstrated that the efficiency of manual laborers decreases as the workday progresses, leading to lower productivity and higher labor costs.

In a similar study Latif et al. (2021) reported that although the operational costs are 6% higher when using mechanized transplantation, it is justified by the increased yield in rice cultivation compared to manual transplantation. Natsis et al. (2011), conducted a study comparing the cost of manual and mechanized transplantation for leeks, cabbage, and peppers, finding that mechanized transplantation ranges from 73% to 86% of the cost of manual transplantation. On the other hand, Ojha and Kwatra (2014) reported a 47% lower cost of mechanized transplantation in rice compared to the traditional manual method.

A larger-scale model was developed by González-Gómez and Morini-Marrero (2009), proposing a mathematical arrangement for determining costs in ornamental plant cultivation in nurseries, considering a greater number of variables to simplify the interpretation of a complex cost model. In the recent trend of generating digital tools for farmers to manage agricultural production more easily and efficiently, various applications have been developed. For example, Sopegno et al. (2016) propose an application that can calculate the costs of certain agricultural activities from a smartphone.

For this to happen, it is necessary to create equations or algorithms like those proposed in the present study, so that the application can calculate and provide information for decision-making. In a study by Holtum et al. (2011), they recommend mechanizing agave production to use it as a raw material for generating biofuel in Australia. On the other hand, Núñez et al. (2011) analyze the costs of producing biofuel from agave in Mexico and concluded that it is necessary to reduce the costs of manual activities, including planting and harvesting, to make it competitive against biofuel from maize or sugarcane. Given the above, particularly for agave cultivation, it is necessary to determine the costs of mechanized transplantation as well as the costs of manual transplantation, considering the value of the agave planting machine prototype that has been developed and the variables involved in the agricultural activity. Knowing the values of these variables will help in making decisions between manual and mechanized transplantation methods.

3. Materials and Methods

It is possible to find two types of plants for agave development: offshoots from the mother plant in the traditional propagation method (Fig 1) and offshoots from micropropagated plants in the nursery (Fig 2), a method provided by biotechnology.

Fig 1: Offshoot from agave plant - Traditional propagation.

Fig 2: Offshoot from agave plant - Biotechnological propagation.

In both cases, the field transplanting work is carried out manually, requiring a significant number of laborers to perform this activity. There is a transplanting machine prototype (Fig 3) for which a commercial value cannot be estimated yet. However, the commercial value of other similar transplanting machines (Fig 4) can be known to make a comparison against the cost of manual transplanting.

Fig 3: Agave Planting Machine Prototype.

Fig 4: Chechi & Magli Planting Machine, Fox drive model, for bare-root plants (C&M, 2022).

3.1. Estimation of the cost of manual transplantation.

To determine the cost of manual transplantation, direct field research was conducted on agave transplantation, and the values shown in Table 1 were obtained. Although there may be slight variations between different areas within the state of Jalisco in Mexico or outside it, especially in the payment to laborers per transplanted plant.

Table 1: Manual transplant cost.

Plants per hectare	3,500	pla ha^{-1}
Unit cost of manual transplantation (PPP)	0.11	US$ pla^{-1}
Cost of manual transplantation (CTMan)	385	US$ ha^{-1}

The unit cost of manual transplantation (PPP) represents the amount paid to the worker for placing 1 plant in the field, and they can reach up to 800 units in a day's work if conditions allow. Similarly, the number of plants per hectare corresponds to a planting scheme with 1 meter spacing between plants and 2.8 meters between rows of agave, an average value for the agave-growing zone in the state of Jalisco. By considering both values, it is possible to establish the equation that predicts the cost of manual transplantation, as described below:

$$CTMan = PPP(3{,}500) \qquad (1)$$

Where;

CTMan = Cost of manual transplantation ($ ha^{-1})
PPP = Unit cost of manual transplantation ($ pla^{-1})
3,500 = Planting density in field (pla ha^{-1})

3.2. Estimation of the cost of mechanized transplantation.

To perform mechanized transplantation, the following is required: an agricultural tractor to move the transplanting machine, the transplanting machine itself, and three workers to feed the planter and supervise and correct any eventuality. Considering the mentioned prototype of the planting machine, a medium-power tractor is estimated to be sufficient for the task. To simplify the analysis, the rental of a tractor was considered the best option, with a value similar to backhoe in civil construction, which has an average cost of US$ 30 h^{-1}. As a second element, the probable price of a mechanical transplanting machine with gripping tongs for a double row, as shown in figure 4, was investigated and estimated at US$ 25,000 per machine. The third element involves the cost of the workers who accompany the tractor-planter assembly. Considering the cost of manual transplantation, the same payment of US$ 0.11 per plant was considered for each of the three workers, and each of them is capable of placing 800 plants per day, resulting in a payment of US$ 88 day^{-1}. With these three values, it is necessary to make an equivalence that allows a comparison in dollar per hectare ($ ha^{-1})

between the cost of manual transplantation and the cost of mechanized transplantation since the tractor rental is expressed in $ h^{-1}, the planter $ $machine^{-1}$, and the cost of the workers in $ day^{-1}.

As a first step, it is necessary to determine the working capacity of the tractor-planter assembly in hours per planted hectare (h ha^{-1}). The variables that influence this phenomenon are the planting spacing and the working speed during transplantation (Gómez et al, 2006), as well as the idle times for turning at the end of each row (Navarro and Cinanni, 2009), which are shown in table 2.

Table 2: Working capacity of tractor-planter unit.

Considered variable	Estimated value
Planting spacing between plants	1 m
Planting spacing between rows	2.8 m
Rows per hectare	35.7
Row length	100 m
Distance to travel	3,571 m ha^{-1}
Distance to travel	3.571 km ha^{-1}
Transplantation working speed	1.1 km h^{-1}
Time per planted hectare	3.25 h ha^{-1}
Downtime (turns at the end of rows)	0.30 h ha^{-1}
Working capacity of tractor-planter unit	3.54 h ha^{-1}

Once the working capacity of the tractor-planter unit is determined, it is possible to calculate the cost in $ per hectare for the tractor, planting machine, and operators. The cost of the tractor for planting a hectare of agave, according to the working capacity, is shown in Table 3.

Table 3: Cost of tractor per hectare

Rent of tractor	30	US$ h^{-1}
Working capacity of the tractor-planter assembly	3.54	h ha^{-1}
Cost of tractor per transplanted hectare	106.2	US$ ha^{-1}

To determine the cost of the machine per planted hectare, we start with the possible estimated commercial value of the agave planting machine prototype shown in Figure 3. We also consider the costs of repair and maintenance (Molenhuis, 2001; Lazarus and Selley, 2005) as a percentage of the machine's acquisition value, the available time in hours per season for agave transplantation that machine can work per year, the machine's useful life (Hunt, 2008), and the field capacity of the tractor-planter unit (Table 3). Table 4 presents the cost of the agave planting machine in dollar per hectare (US$ ha^{-1}).

Table 4: Cost of agave planting machine per hectare planted.

Transplanter machine value	US$ 25,000 mach^{-1}
Maintenance and repair cost (40% of the cost)	US$ 10,000 mach^{-1}
Working capacity per day (8 hours per day)	2.26 ha day^{-1}
Working capacity per week (6 days)	13.5 ha week^{-1}
Working capacity per month (4 weeks)	54.2 ha month^{-1}
Working capacity per season (4 months)	217 ha season^{-1}
Working capacity per season (in hours)	768 h season^{-1}
Planting machine's useful life	1,200 h mach^{-1}
Working capacity per machine's seasons	1.56 season mach^{-1}
Cost per hour of the agave planting machine	US$ 29.16 h^{-1}
Tractor-planter working capacity	3.54 h ha^{-1}
Cost per hectare of the planting machine	US$ 103.24 ha^{-1}

Finally, it is necessary to incorporate the labor cost, given that the prototype of the planting machine requires assistance from two operators to perform the activity, plus one operator at the field level to accompany the tractor-planter unit and supervise and correct any planting issues. It should be noted that planting machines typically achieve an average efficiency of 90% in transplantation, with 95% being very good and anything lower than 80% considered unacceptable (Aykas et al., 2017). Therefore, considering that the tractor-planter unit requires three operators, the cost in dollar per hectare (US$ ha^{-1}) of labor to assist the mechanized transplantation is determined, as shown in Table 5.

Table 5: Cost of operators per planted hectare.

Unit cost of manual transplantation	US$ 0.11 plant^{-1}
Working capacity of 1 laborer	800 plants day^{-1}
Number of operators to assist the agave planting machine	3 operators day^{-1}
Working hours per workday	8 h day^{-1}
Working capacity of the tractor-planter unit	3.54 h ha^{-1}
Labor cost per hectare	US$ 116.82 ha^{-1}

Based on the variables described earlier, the equation (Equation 2) that predicts the cost of mechanized transplantation is presented as follows:

$$CTMec = 3.54\left[V_{mach}\left(\frac{1.4}{1200}\right) + R_{trac} + PPP(300)\right] \qquad (2)$$

Where;

CTmec = Cost of mechanized transplantation ($\$\ ha^{-1}$)

3.54 = Working capacity of the tractor-planter unit ($h\ ha^{-1}$)

Vmach = Price or commercial value of the agave planting machine ($\$\ mach^{-1}$)

Rtrac = Rental cost of agricultural tractor ($\$\ h^{-1}$)

PPP = Unit cost of manual transplantation ($\$\ pla^{-1}$)

1.4 = Transplanting machine value plus 40% of repair and maintenance along useful life

1 200 = Hours of useful life

300 = Represents plants factor that operators can reach working on transplanter ($pla\ h^{-1}$)

The decision criterion for choosing between manual or mechanized transplantation is presented in the following relation. If the cost of mechanized transplantation is less than or equal to the cost of manual transplantation, its choice is justified.

$$CTMec \leq CTMan$$

3.3. Machine value recovery.

If the price of the machine increases, the savings will be reduced, extending the time it takes to recover the investment. However, the recommended useful life of 1,200 hours for this type of machinery sets a time limit, as the economic analysis may predict several hours that the machine would be unable to achieve due to this criterion. Considering this limitation, it is convenient to determine an equation (Equation 3) that indicates the maximum value the machine should have when reaching the threshold: useful life in hours. The following equation determines the recovery in working hours of the machine by dividing the machine's value by the savings obtained from the difference between the cost of mechanized transplantation and manual transplantation, multiplied by the working capacity of the tractor-planter unit.

$$VRH = -\frac{V_{mach}}{CTMec - CTMan} \times 3.54 \qquad (3)$$

Where;

VRH = Value recovery in hours

Another expanded form of Equation 3 is presented below, where CTMec and CTMan have been replaced, respectively, with Equation 4:

$$VRH = -\frac{Vmach}{3.54\left[Vmach\left(\frac{1.4}{1200}\right) + Rtrac + PPP\,(300)\right] - PPP\,(3500)} \times 3.54 \qquad (4)$$

The correct way to solve Equation 4 is through iteration by assigning a machine value to determine VRH. The maximum value should be reached when VRH approaches the threshold of 1,200 hours, which represents the machine useful life.

4. Results

The cost of manual transplantation (CTMan) amounts to US$ 385 ha^{-1} (Table 1), while the cost of mechanized transplantation (CTMec) results in US$ 326.27 ha^{-1}. The latter includes: the cost of tractor rental amounting to UD$ 106.2 ha^{-1} (Table 3); the cost of the machine at US$ 103.25 ha^{-1} (Table 4); and the cost of operators at US$ 116.82 ha^{-1} (Table 5), all this considering a commercial value of US$ 25,000 per machine. The saving between mechanized and manual transplantation amounts to US$ 58.73 per hectare, justifying the choice of mechanized transplantation.

In terms of percentage, mechanized transplantation represents 85% of the cost compared to manual transplantation. When reviewing the savings per hectare and comparing it with the acquisition value of a machine, along with maintenance and repair costs, it is necessary to plant 596 hectares to recover the investment in one planting machine. This represents 2.75 seasons (years), considering the working capacity per season of 217 hectares that the planter can achieve (Table 6).

Table 6: Comparison of mechanized versus manual transplantation.

Savings of mechanized transplantation over manual	US$ 58.73 ha^{-1}
Cost of mechanical transplantation versus manual	85%
Commercial value of the machine and maintenance cost	US$ 35,000 $mach^{-1}$
Hectares required to recoup the investment in one machine	596 ha $mach^{-1}$
Working capacity per season (4 months)	217 ha $season^{-1}$
Seasons (years) to recoup the investment of the planter	2.75 seasons $mach^{-1}$

If we substitute US$ 385 as the maximum value in Equation 2 (CTMec) and solve for the unknown variable "Vmach", considering US$30 as the tractor rental cost (Rtrac) and US$0.11 as the unit cost of manual transplantation (PPP), the maximum value the planting machine should be US$ 39,220.35. The costs of mechanized transplantation in $ ha^{-1} by iterating the variable "machine value" in intervals of US$ 5,000 up to a maximum value of US$ 50,000, comparing it against CTMan and the decision criterion, are shown in Table 7.

Tabla 7: Cost of mechanized transplanting vs manual transplanting of agave.

Machine US$ $mach^{-1}$	Cmach US$ ha^{-1}	Rtrac US$ ha^{-1}	Coper US$ ha^{-1}	CTmec US$ ha^{-1}	CTman US$ ha^{-1}	CTMec ≤ CTMan US$ ha^{-1}
5,000	$21	$106	$117	$244	$385	-$141
10,000	$41	$106	$117	$264	$385	-$121
15,000	$62	$106	$117	$285	$385	-$100
20,000	$83	$106	$117	$306	$385	-$79
25,000	$103	$106	$117	$326	$385	-$59
30,000	$124	$106	$117	$347	$385	-$38
35,000	$145	$106	$117	$368	$385	-$17
40,000	$165	$106	$117	$388	$385	$3
45,000	$186	$106	$117	$409	$385	$24
50,000	$207	$106	$117	$430	$385	$45

The payback of the machine price, according to the hours of work performed, using Equation 4 (RHT) with values ranging from US$ 5,000 to US$ 50,000 in US$ 5,000 intervals, is presented in Table 8. Between US$ 20,000 and US$ 25,000 is found the maximum value that the machine should have when it reaches the threshold of its 1200 hours useful life. The results of the interpolation method shows that the machine price should not exceed $450,081 to be recovered within its useful life. As mentioned earlier, a machine value below US$ 39,220.35 justifies mechanized transplantation compared to manual, but above US$ 22,500, the machine's useful life is exceeded, requiring a new acquisition.

Tabla 8: Machine cost payback (VRH)

Machine price ($ mach^{-1})	CTMec ≤ CTMan (US$ ha^{-1})	Payback (ha)	Payback (season)	Payback (h)
5,000	-141	35	0.16	125
10,000	-121	83	0.38	293
15,000	-100	150	0.69	531
20,000	-79	252	1.16	892
25,000	-59	426	1.96	1,507
30,000	-38	788	3.63	2,789
35,000	-17	2,008	9.25	7,108
40,000	3	- 12,422	- 57.25	- 43,975
45,000	24	- 1,885	- 8.69	- 6,674
50,000	45	- 1,123	- 5.18	- 3,976

5. Discussion

The results show that from an economic standpoint, mechanized agave transplantation in the field is feasible, and up to a certain machine price, its choice is justified over manual transplantation. This aligns with the findings of Aykaz E. et al (2017), who recommend the use of transplanters for vegetables instead of relying on manual labor in the traditional method. It was determined that the cost of mechanized transplantation represents 85% of the cost of manual transplantation, a value similar that reported by Natsis et al. (2011) in their study comparing the costs of manual and mechanized transplantation for leeks, cabbage, and peppers. Similar conclusions are drawn from the findings of Ojha and Kwatra (2014), regarding the cost of mechanized transplantation being lower than manual transplantation, although the percentage of savings differs, being nearly 50% in the case of rice. The equations developed here allow the calculation of the cost of mechanized transplantation if the variables of tractor rent, machine value, and labor fees are known. The mathematical model proposed here can be used as the basis for programming an application or complementary tool that calculates the cost of mechanized transplantation, the investment recovery in machine working hours, or the maximum machine value that should be paid to recover the investment within the machine's useful life. Such an application could follow the concept proposed by Sopegno et al. (2016), where agricultural costs can be calculated using a smartphone application.

6. Conclusions

A set of equations were stablished to allows estimation costs for mechanized and manual transplantation of agave, as well as a decision criterion to choose between mechanized and traditional manual methods. With this mathematical model, the recommended maximum machine value can be calculated at any given time, as the prices of the variables involved in the phenomenon change. The variables influencing the phenomenon are the machine's value, agricultural tractor lease cost, and payment per plant to the operators. By knowing these data, it is possible to determine the maximum price the planting machine should have to recover the investment within its useful life. After the analysis presented here, the maximum price that the prototype of the agave planting machine should be US$ 22,500.

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