

FACTORS AFFECTING THE ADOPTION OF SHADE CLOTH TECHNOLOGY IN APPLE PRODUCTION IN MEXICO

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ABSTRACT

The vulnerability of apple tree (*Malus domestica* Borkh.) yield to changes in climatic variables justifies an examination of the determining factors in producer technology adoption. The main factors are age, orchard size, temperature, and the cost of shade cloth, fertilizers, and labor. The objective of this research was to analyze the factors that influence the adoption rate of shade cloth as protection for apple crops. Municipal-level data was used to estimate a grouped logistic model with the 24 municipalities in which shade cloth was used in 2022. The dependent variable was the adoption rate of shade cloth, and the independent variables were age, farm size, shade cloth price, fertilizers, labor, and temperature. The results show that when age, farm size, and temperature increase by 10 %, the probability of using shade cloth increases by 22.6, 15.7, and 7.6 %, respectively. A 10 % increase in the prices of shade cloth, fertilizers, and labor reduced the probability of shade cloth use by 1.7, 29.8, and 27.3 %, respectively. The adoption rate of shade cloth may increase as the size of the orchard expands through the rental or purchase of land, but it decreases to a greater extent with increases in fertilizer and labor prices. Among the benefits of using shade cloth are the protection of crops from excessive radiation and temperature increases.

Keywords: income per hectare, *Malus domestica* Borkh., logit model, probability, adoption rate, temperature.

INTRODUCTION

Apples (*Malus domestica* Borkh.) have become one of the most popular fruits in Mexico, thanks to changes in consumer tastes. The current trend toward healthy eating led to an increase in apple consumption from 643 698 to 1 112 246 Mg between 1994 and 2022. Over the last three decades, apple production in Mexico has increased from 487 698 to 817 806 Mg (Table 1). This was made possible by the transition from

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Table 1. Evolution of the apple market (*Malus domestica* Borkh.) in Mexico from 1994 to 2022.

Year	Surface ha	Production Mg	Yield Mg ha ⁻¹	Imports Mg	Exports Mg	FTB Mg	ADC Mg
	1	2	3	4	5	6 = 5 - 4	7 = 2 + 4 - 5
1994	61 472	487 698	7.93	156 110	110	-156 000	643 698
1999	64 474	449 867	6.98	136 380	300	-136 080	585 947
2004	59 095	572 906	9.69	154 050	243	-153 807	726 713
2009	56 992	561 493	9.85	222 208	253	-221 955	783 448
2014	55 447	716 865	12.93	235 502	305	-235 197	952 062
2019	52 981	761 483	14.37	252 223	606	-251 617	1 013 100
2022	54 959	817 806	14.88	295 183	743	-294 440	1 112 246
AAGR (%)	-0.40	1.86	2.27	2.30	7.06	2.33	1.97

FTB: foreign trade balance; ADC: apparent domestic consumption; AAGR: average annual growth rate for the period 1994–2022. The analysis was elaborated using data from SIAP (2024) and FAO (2023).

backyard orchards to technified orchards with traditional or introduced varieties and innovations in production management (Favret-Tondato, 2012).

Almost all the apples produced are destined for the domestic market. Production grew at an annual rate of 1.86 % from 1994 to 2022, which is lower than the consumption growth rate of 1.97 %. To satisfy domestic demand, imports increased from 156 110 in 1994 to 295 183 Mg in 2022; in turn, the share of imports for consumption increased from 21 to 26.5 % in the same period (FAO, 2023). Exports are minimal and account for only 0.06 % of total production; hence, the trade balance is in deficit (Table 1). Farmland has expanded over the last 20 years, which has led to an increase in agricultural production (Potapov *et al.*, 2022). However, in the case of apples in Mexico, the area planted has decreased over the last 30 years, from 61 472 ha in 1994 to 54 959 ha in 2022. Therefore, the increase in production was due to an increase in yield per hectare, from 7.93 Mg ha⁻¹ in 1994 to 14.88 Mg ha⁻¹ in 2022 (SIAP, 2024).

Most apple production is concentrated in the north of the country. The states of Chihuahua and Coahuila account for 85 and 5.3 % of the total national production (SIAP, 2024). Puebla accounts for 4.4 %, but 66 % of the area is planted with native apples, which has an impact on producers' income, as the average rural price of native apples (4610.00 MXN Mg⁻¹ in 2022) was 2.2 times lower than that of Golden Delicious apples (11 039.95 MXN Mg⁻¹ in 2022) (SIAP, 2024). Production in the municipalities of Cuauhtémoc, Guerrero, and Namiquipa, Chihuahua, exceeds 23 Mg ha⁻¹. In Coahuila, apple trees are only planted in the municipality of Arteaga, and their irrigated yields reach 8.9 Mg ha⁻¹ (SIAP, 2024). In the north of the country, integrated crop management is practiced, with varieties of higher market value developed according to the local climate. Some orchards are protected with shade cloth against solar radiation, hail, and late frosts (Favret-Tondato, 2012).

Socioeconomic, technological, and environmental factors influence the adoption rate of shade cloth. A study on the adoption of crop protection measures such as anti-hail netting conducted in India found that adoption is positively influenced by age, income, and property size, as producers have accumulated more wealth over time and find it easier to invest in crop protection (Prakash *et al.*, 2021). In turn, Shashikala *et al.* (2022) found that income and property size are positively related to protective netting adoption rates, but age is negatively related. The adoption rate of shade cloth is limited by investment, production, and labor costs, so including government subsidies may be an alternative to increase their use (Prakash *et al.*, 2020). The need to protect investment in perennial crops from temperature increases due to climate change also increases the likelihood for producers to adopt protective measures (Gunathilaka *et al.*, 2018).

Currently, the global apple business faces challenges such as international competition and low product quality. Climate change affects the quantity and quality of natural resources due to variations in temperature, precipitation, winds, and water availability for crop growth and reproduction (Giacinti, 2003). Overexposure to sunlight and high temperatures affects plant and fruit development through physiological disorders (Severino *et al.*, 2023). In South Africa, fruit quality problems have arisen due to sunburn, resulting from high temperatures with excessive solar intensity, leading to a decrease in export volumes of up to 50 % (Wand and Gindaba, 2005).

Porsch *et al.* (2018) point out that, in Germany, losses due to frost and hail are the most significant sources of risk in technified orchards and recommend the use of netting, even in places where hailstorms are not a regular occurrence. Protected agriculture in apple orchards is widely used in Europe and has spread throughout the world in the last 30 years. Depending on the type of protection, it fulfills various functions such as reducing sunburn, hail damage, and wind damage (Noè and Eccher, 1996).

In Brazil, do Amarante *et al.* (2011) found positive effects in the use of white netting in apple orchards to reduce sunburn and rot after cold storage. However, the fruit lost color and pulp firmness, and the starch index increased. In Mexico, low-tech producers are mainly affected by late frosts, with a loss of up to 70 % of the number of fruits per tree, because they are unable to mitigate the risk due to lack of resources and technical assistance (Ramírez-Legarreta *et al.*, 2006).

It is believed that apple production and quality can be improved by adopting crop protection technologies. Therefore, this study aimed to analyze how population age, orchard size, temperature, and the prices of shade cloth, fertilizers, and labor affect the adoption rate of shade cloth technology in apple cultivation. The study was based on economic theory, so the hypothesis is that increases in age, size of the production units, and temperatures have positive effects on technology adoption. On the other hand, the price of shade cloth, fertilizers, and labor has negative effects as they add to the production cost.

MATERIALS AND METHODS

Based on Gujarati and Porter (2010), a grouped logit model (glogit) was formulated to determine the factors affecting the adoption rate of shade cloth technology in apple production, which was estimated using the Statistical Analysis System (SAS) 9.0 program (SAS Institute Inc., Cary, NC, USA). By using this model with municipal-level data, the proportion of shade cloth use can be estimated by adding the area that uses this technology and the area that does not. As a result, each observation (group) concentrates the total number of cultivated hectares where the technology is used or not; therefore, the total universe of municipalities that use shade cloth is considered. The dependent variable was the rate of adoption of shade cloth or, conversely, open-air planting. This was defined as the probability of using shade cloth in municipality i and was calculated following these steps (Equations 1 and 2):

$$P_i = TUMS_i = \frac{SMS_i}{ST_i} \quad (1)$$

$$1 - P_i = \frac{ST_i - SMS_i}{ST_i} \quad (2)$$

where, for municipality i , P_i is the probability of using shade cloth in i and $1-P_i$ is the probability of not using it (planting outdoors); $TUMS_i$ is the rate of shade cloth use in i ; SMS_i is the area cultivated with shade cloth in i ; and ST_i is the total area harvested in i . The grouped logit model was formulated, in which the qualitative dependent variable becomes an odds ratio. The proposed model is:

$$L_i = \ln\left(\frac{P_i}{1 - P_i}\right) = \beta_1 + \beta_2 EDA_i + \beta_3 TAM_i + \beta_4 PMP_i + \beta_5 PMO_i \\ + \beta_6 PFE_i + \beta_7 TMI_i + u_i \quad (3)$$

where, for each municipality i , L_i is the natural logarithm of the odds ratio $[P_i/(1-P_i)]$, EDA_i is the average age of the population over 15 years (in years), TAM_i is the size of the orchard (in ha), PMP_i is the price of protective netting (in MXN ha⁻¹), PMO_i is the price of labor (in MXN per day), PFE_i is the price of fertilizer (in MXN Mg⁻¹), TMI_i is the average minimum temperature (in °C), and u_i is the error term, which is asymptotically normally distributed, with mean = 0 and variance = $1/[ST_i P_i (1-P_i)]$, so the disturbance term in the logit model is heteroscedastic (Theil, 1970).

To solve the problem of heteroscedasticity, Gujarati and Porter (2010) propose using weighted least squares; therefore, Equation 3 becomes:

$$\begin{aligned} \sqrt{w_i}L_i = & \beta_1\sqrt{w_i} + \beta_2\sqrt{w_i}EDA_i + \beta_3\sqrt{w_i}TAM_i + \beta_4\sqrt{w_i}PMP_i + \\ & \beta_5\sqrt{w_i}PMO_i + \beta_6\sqrt{w_i}PFE_i + \beta_7\sqrt{w_i}TMI_i + \sqrt{w_i}u_i \end{aligned} \quad (4)$$

or

$$L_i^* = \beta_1\sqrt{w_i} + \beta_2EDA_i^* + \beta_3TAM_i^* + \beta_4PMP_i^* + \beta_5PMO_i^* + \beta_6PFE_i^* + \beta_7TMI_i^* + v_i \quad (5)$$

where $\sqrt{w_i} = \sqrt{ST_i P_i (1 - P_i)}$, EDA_i^* is the weighted average age of the population over 15 years of age, TAM_i^* is the weighted size of the orchard, PMP_i^* is the weighted price of protective netting, PMO_i^* is the weighted price of labor, PFE_i^* is the weighted price of fertilizer, TMI_i^* is the weighted average minimum temperature, and v_i is the weighted error term.

The model analysis was performed as an unweighted logit by dividing L_i^* by the weight $\sqrt{w_i}$. Subsequently, the ratio of predicted probabilities was obtained using the antilogarithm of L_i^* (Equation 6):

$$e^{\hat{L}_i} = \frac{\hat{P}_i}{1 - \hat{P}_i} \quad (6)$$

The predicted probability of using shade cloth technology is obtained by solving for \hat{P}_i in Equation 6, resulting in Equation 7:

$$\hat{P}_i = \frac{e^{\hat{L}_i}}{1 + e^{\hat{L}_i}} \quad (7)$$

The unweighted and weighted estimated probabilities were obtained for each municipality. Using the latter, the total average probability of the adoption rate of shade cloth technology was calculated using Equation 8:

$$P_p = \sum_{i=1}^I [\hat{P}_i \times \delta_i] \quad (8)$$

where P_p is the total average probability of using shade cloth, $\delta_i = ST_i/ST$ is the share of region i in the total area planted with apple trees, and I is the total number of municipalities used in the model.

To obtain the total area planted with apple trees, municipal data reported by SIAP (2024) in 2022 was used. The area planted with shade cloth was obtained from the area planted with shade cloth for perennial crops in the 2022 Agricultural Census (INEGI, 2023). The procedure for obtaining the total planted area was as follows: a) The main apple-producing municipalities in the country were selected; b) The municipal area planted with shade cloth for perennial crops was obtained; and c) It was verified that the total area with shade cloth matched the state data reported in the census.

Using information from SIAP (2024), 340 producing municipalities were identified in the country, with a total planted area of 57 817 ha (Table 2). Municipalities with more than 100 ha planted were used as the grouping criterion. Of the 340 municipalities, 289 had an area of less than 100 ha, while 51 municipalities, distributed across Chihuahua, Coahuila, Durango, Nuevo León, Sonora, Zacatecas, Querétaro, Hidalgo, Veracruz, Puebla, and Chiapas, had an area greater than 100 ha (Table 2). According to the 2022 National Agricultural Census, shade cloth is used in 24 municipalities, so the model estimate was based solely on data from those municipalities (INEGI, 2023). The total area considered was 47 631 ha planted, representing 82.4 % of the national total, of which 9401 ha use shade cloth (Table 2). The adoption rate of shade cloth in these 24 municipalities is 19.7 %.

The average size of orchards at the municipal level was calculated using data from the 2022 Agricultural Census (INEGI, 2023). The area planted with perennial crops was divided by the number of production units. In municipalities that use shade cloth, 82 % of orchards are apple orchards, meaning they specialize in this crop. It was considered that apple producers can increase the size of their farms by renting or purchasing land from other apple producers, which means that the total area remains constant.

For the price of shade cloth, the price (MXN Mg⁻¹) of apples produced was used (Equation 9). The cost of the netting per hectare is fixed, as it is part of the orchard establishment and is the same regardless of the apples produced. Productivity (measured by yields) determines the price of shade cloth; that is, in orchards with low yields, the cost of the netting is higher and vice versa. In addition, different types of netting, the location of the municipalities, and the diversity of use determine the variability in prices. This way, the price reflects the effect of productivity and avoids price variability.

$$PMS_i = \frac{CMS}{R_i} \quad (9)$$

where, for municipality i , PMS_i is the price of shade cloth (in MXN Mg⁻¹ in 2022), CMS is the cost of shade cloth quoted in Mexico City with a national distributor (in MXN ha⁻¹), and R_i is the yield level (in Mg ha⁻¹ in 2022).

The price of labor was selected because of its importance in the apple production process, which is labor intensive, especially during the fruit thinning and harvesting phases. The data were obtained from the 2022 Agricultural Census daily wage data

Table 2. Area planted with apple trees (*Malus domestica* Borkh.) using shade cloth in Mexico by municipality in 2022.

Number	State	Municipality	Planted area (ha)	Surface with shade cloth (ha)	Number of municipalities	Adoption rate (%)
Municipalities with more than 100 ha planted using shade cloth						
1	Chihuahua	Cauhtémoc	10 581	4053	1	38.30
2	Chihuahua	Guerrero	8914	1647	1	18.48
3	Chihuahua	Namiquipa	5151	736	1	14.29
4	Chihuahua	Bachíniva	2763	212	1	7.67
5	Chihuahua	Cusihuirachi	2599	1616	1	62.18
6	Chihuahua	Carichí	913	135	1	14.79
7	Chihuahua	Riva Palacio	700	261	1	37.29
8	Chihuahua	Gran Morelos	209	125	1	59.81
9	Chihuahua	Guachochi	129	1	1	0.78
10	Coahuila	Arteaga	5792	466	1	8.05
11	Durango	Canatlán	3057	26	1	0.85
12	Durango	Nuevo Ideal	1156	2	1	0.17
13	Durango	San Dimas	300	2	1	0.67
14	Durango	Pueblo Nuevo	256	9	1	3.52
15	Hidalgo	Acaxochitlán	151	1	1	0.66
16	Hidalgo	Zimapán	150	1	1	0.67
17	Nuevo León	Santiago	624	1	1	0.16
18	Nuevo León	Galeana	557	40	1	7.18
19	Puebla	Zacatlán	1882	25	1	1.33
20	Puebla	Tlachichuca	534	21	1	3.93
21	Puebla	Chignahuapan	422	15	1	3.55
22	Querétaro	San Joaquín	200	1	1	0.50
23	Sonora	Yécora	207	4	1	1.93
24	Veracruz	Jalacingo	384	1	1	0.26
Subtotal (1–24)	-	-	47 631	9401	24	19.74
Municipalities with more than 100 ha planted without shade cloth						
Subtotal (25–51)	Several [†]	-	5571	0	27	0.00
Municipalities with less than 100 ha planted (none use shade cloth)						
Subtotal (52–340)	Several [‡]	-	4615	0	289	0.00
Nationwide total	-	-	57 817	9401	340	16.26

[†]The 27 municipalities are located in the states of Chiapas, Chihuahua, Durango, Hidalgo, Puebla, Querétaro, Veracruz, and Zacatecas. [‡]The 289 municipalities are located in the states of Aguascalientes, Baja California, Chiapas, Chihuahua, Mexico City, Coahuila, Durango, Guanajuato, Guerrero, Hidalgo, Jalisco, State of Mexico, Michoacán, Morelos, Nuevo León, Oaxaca, Puebla, Querétaro, San Luis Potosí, Tlaxcala, Veracruz, and Zacatecas. Prepared with information obtained from INEGI (2023) and SIAP (2024).

(INEGI, 2023). For fertilizers, the frequent price for 2022 (SNIIM, 2024) at the nearest supply center in each producing municipality was used. Fertilizers are part of the technology bundle, which means that an increase in their price affects the adoption of the technology, as it raises the cost of production (García-Salazar *et al.*, 2023). For age,

the population average over 15 years of age from the 2020 Population and Housing Census (INEGI, 2021) was used. This variable includes apple producers, possible family labor, and wage earners involved in the production process.

To measure the effect of temperature on shade cloth adoption, the average annual minimum temperature for 2022 was used (CONAGUA, 2023). Temperature increases have different effects on apple tree development: in cold regions, flowering could be brought forward by late frosts, and in temperate climates, the cold period requirement would be incomplete, delaying the flowering phase and leading to poor fruit setting and final yield (Funes *et al.*, 2016). Furthermore, rising temperatures increase the frequency of severe hailstorms, putting crops at risk (Martín *et al.*, 2024).

For statistical analysis, the means, minimums, and maximums of each variable were used. For economic analysis, the following hypothetical scenarios were considered, taking into account the evolution of the independent variables over the last 10 years: a) An increase of 5, 10, and 15 % in the age of the population; b) An increase of 10, 20, and 30 % in the size of the property; and c) An increase of 5, 10, and 15 % in the price of shade cloth, fertilizers, labor, and temperature. The percentage of land suitable for integrating technology was estimated based on the share of irrigated land in the nationwide total.

RESULTS AND DISCUSSION

The model adequately explains the determining factors for the adoption of shade cloth technology. The coefficient of determination (R^2) was 0.95, indicating that the independent variables explain 95 % of the dependent variable, thus suggesting that there is little influence from other variables not explicitly included in the model. The Fisher significance test (F) had a value of 48.49 (Prob > F less than 0.05), so the correlation between the endogenous and exogenous variables is statistically significant and different from zero at $\alpha = 0.05$ (Table 3).

Table 3. Estimated statistical parameters of the glogit model for the adoption rate of shade cloth in apple orchards (*Malus domestica* Borkh.).

Variable	Parameter	Standard errors	<i>t</i> value	Prob > <i>t</i>
$\sqrt{w_i}$	5.19	4.10	1.27	0.22
EDA*	0.07	0.04	1.83	0.09
TAM*	0.11	0.02	7.13	<0.01
PMP*	-0.0001	0.00004	-3.03	0.01
PMO*	-0.02	0.01	-2.94	0.01
PFE*	-0.0004	0.0001	-2.46	0.02
TMI*	0.28	0.04	7.38	<0.01
R ²	0.95			
F	48.49	Prob > F	<0.01	

EDA*: average age of the population over 15 years old, TAM*: size of the orchard, PMP*: price of protective netting, PMO*: price of labor, PFE*: price of fertilizer, TMI*: average annual minimum temperature.

The model underwent statistical testing for validation. Based on the Breusch-Pagan test, it was concluded that there was no heteroscedasticity in the variance of the error term transformed to an $\alpha = 0.05$. The individual t-tests of the variables orchard size, netting and labor costs, fertilizers, and minimum temperature were significant at $\alpha = 0.05$, while population age was significant at $\alpha = 0.1$. The multicollinearity test was performed using the auxiliary regression method, and no significant collinearity between the independent variables was found. The coefficients of the independent variables had the expected sign. The parameters for producer age, orchard size, and temperature had a positive sign. The parameters for shade cloth prices, labor, and fertilizer have a negative sign.

Statistical analysis showed mixed results in terms of orchard size, mesh prices, fertilizers, and labor (Table 4). In municipalities where shade mesh is used, orchard size was 2.97 ha larger than the average for municipalities with more than 100 ha planted with apples. The minimum and maximum values indicate that there are still municipalities with small-scale backyard production as well as large-scale units. The average price of shade cloth in municipalities that use it was 18.6 % higher than the overall average, and the minimum price was obtained in highly productive units. The average price of fertilizers was 7.3 % lower in municipalities that use shade cloth compared to the overall average. The difference between the minimum and maximum values for this last aggregate was 98.2 %, indicating high variability in these prices at the municipal level. In apple-producing municipalities in the north, labor is paid higher than in the rest of the country. The highest daily wage was in Tamazula, Durango, while the lowest was in Chenalhó, Chiapas.

The model was validated with empirical data using the average probability of adoption by municipalities that use shade cloth (Table 5). The estimated total average probability (0.203) was close to the observed value (0.197). The estimated area of land cultivated with shade cloth was similar (9618 ha) to the observed area (9401 ha),

Table 4. Statistical indicators of the glogit model of the adoption rate of shade cloth (n = 24) in apple orchards (*Malus domestica* Borkh.).

Variable	Municipalities with over 100 ha planted			Municipalities using shade cloth		
	Average	Minimum value	Maximum value	Average	Minimum value	Maximum value
EDA* (years)	39.94	33.55	48.79	40.84	36.85	48.79
TAM* (ha)	5.59	0.25	32.61	8.56	0.33	32.61
PMP*	11 616.00	1866.00	43 000.00	13 772.76	1866.32	43 000.00
PMO* (daily MXN)	231.62	95.50	378.50	257.92	174.00	320.00
PFE* (MXN Mg ⁻¹)	17 951.00	12 375.00	24 533.00	16 733.10	12 390.42	20 925.83
TMI* (°C)	8.13	2.17	17.10	7.44	2.17	15.83

EDA*: average age of the population over 15 years, TAM*: orchard size, PMP*: price of protective netting, PMO*: price of labor, PFE*: price of fertilizer, TMI*: minimum annual average temperature.

Table 5. Effect of changes in independent variables on the adoption of shade cloth in apple cultivation (*Malus domestica* Borkh.).

Variable	Average total probability	Area cultivated with netting (ha)	Change [†] (%)	Area with potential (ha)	Cultivated area without netting (ha)	Change [‡] (%)
Data observed	0.197	9401		38 535	29 134	-
Base scenario (estimated data)	0.203	9652		38 535	28 883	-
Change in the independent variables						
EDA increases:						
5 %	0.222	10 595	9.773	38 535	27 940	-3.266
10 %	0.243	11 592	20.102	38 535	26 943	-6.717
15 %	0.265	12 640	30.959	38 535	25 895	-10.346
TAM increases:						
10 %	0.231	11 014	14.110	38 535	27 522	-4.715
20 %	0.261	12 450	28.992	38 535	26 085	-9.688
30 %	0.293	13 936	44.386	38 535	24 599	-14.832
PMP increases:						
5 %	0.201	9554	-1.016	38 535	28 981	0.340
10 %	0.199	9459	-1.999	38 535	29 076	0.668
15 %	0.197	9367	-2.954	38 535	29 168	0.987
PMO increases:						
5 %	0.157	7484	-22.462	38 535	31 051	7.506
10 %	0.119	5687	-41.084	38 535	32 849	13.729
15 %	0.089	4246	-56.009	38 535	34 289	18.716
PFE increases:						
5 %	0.166	7888	-18.271	38 535	30 647	6.106
10 %	0.134	6362	-34.088	38 535	32 174	11.391
15 %	0.106	5069	-47.484	38 535	33 467	15.868
TMI increases:						
5 %	0.218	10 382	7.568	38 535	28 153	-2.529
10 %	0.234	11 137	15.390	38 535	27 398	-5.143
15 %	0.250	11 914	23.431	38 535	26 622	-7.830

[†]Change relative to the netted area in the base scenario. [‡]Change relative to the unnetted area in the base scenario. EDA*: average age of the population over 15 years old, TAM*: orchard size, PMP*: price of protective netting, PMO*: price of labor, PFE*: price of fertilizer, TMI*: average annual minimum temperature.

with a difference of 251 ha or 2.7 % of the observed value, allowing for the creation of scenarios to analyze the effects of changes in the adoption rate of shade cloth in response to changes in the explanatory variables.

The results showed a positive relationship between population age and the adoption of technology, as found by Adams *et al.* (2021) in Ghana. The average age in municipalities where shade cloth is used was 40.84 years, which is lower than the average of 48.6 years observed among agricultural workers (SE, 2024). According to the estimated average probabilities, with a 15 % increase in the age of the population in all apple-producing regions, the total average probability of adopting shade cloth increases from 0.203

to 0.265. In absolute terms, the protected area would increase to 12 640 ha, and the area without shade cloth would decrease by 11.62 %. In a study on apples in Puebla, Mexico, Peraza-Reyes *et al.* (2020) found a positive relationship between the age of producers and the decision to incorporate technological innovations. Younger farmers tend to be less risk-averse and are willing to try new technologies (Gelgo, 2016), so apple growers will find it easier to transition from open-air to protected agriculture. The average size of the orchard is a variable that had a positive impact on the adoption of shade cloth. A 30 % increase in size would raise the probability of using shade cloth from 0.203 to 0.293; that is, the protected area would be 14 369 ha, and the unprotected area would decrease by 14.8 %. Kolady *et al.* (2021) found a positive relationship between the adoption rate of precision agriculture and farm size. This is because larger production units have more capacity to generate economies of scale by purchasing inputs in bulk and have easier access to credit, technology, and technical assistance. In addition, small associated producers can access better technologies, given that the small size of their production units makes access difficult (Ma *et al.*, 2018).

The relationship between the price of the mesh and the adoption rate was negative. Given a 15 % increase in this variable in all municipalities, producers would stop purchasing shade mesh to protect their crops, which would reduce the utilization rate to 0.197. This would increase the area without shade mesh by 0.83 % compared to the base scenario. The results are consistent with García-Salazar *et al.* (2018), who found a negative relationship between the price of the technology and the adoption rate. In their analysis, a 15 % reduction in price would decrease the area without use of the technology by 5.3 %. This decline is caused by the law of demand, since increasing the price of shade cloth decreases the use of the product and therefore its adoption rate, and vice versa.

One of the most important factors in the adoption rate of shade cloth was the price of labor. According to the results, when labor costs increase by 15 %, the adoption rate drops to 0.089. Increases of this magnitude would reduce the adoption rate by up to 56 %. This variable has a negative impact on the adoption of this technology because administrative and labor costs limit producers' ability to incorporate technological innovations on their farms, especially when crops are labor-intensive (Fernández-Reyes and Restrepo-Franco, 2023), as is the case of apple production.

The price of fertilizers had an indirect relationship with the rate of technology adoption. A 10 % increase in price in all municipalities using shade cloth would reduce the average total probability of adoption to 0.134 and the protected area by 11.4 %. Similar results were reported by García-Salazar and Guzmán-Soria (2015), who found that a 10 % decrease in the price of inputs increases the rate of technology adoption by 17.5 %. Increases in input prices have a negative effect on the utilization rate because apple producers tend to prioritize their budget on the purchase of fertilizers rather than crop protection.

The use of shade cloth is a protective measure to control environmental factors in apple production. That is why temperature was a determining factor in the adoption

rate. The relationship between both variables was positive, where a 15 % increase in temperature increases the probability of use to 0.25. This decreased the area without shade cloth by 7.8 % compared to the base scenario. García-Salazar *et al.* (2023) found the same relationship between temperature and the adoption rate of technified irrigation systems in Mexico, although with more accentuated increases of up to 20 %. The effects of the variable on the use of shade cloth are modest, which may be due to growers' lack of knowledge of the advantages of using the correct shade cloth on plant physiology and yield. It is considered that, when faced with increases in temperature, producers take action to protect their investment in their crops.

CONCLUSIONS

The adoption rate of shade cloth technology in apple production is positively correlated with population age and orchard size. Young producers have easier access to this technology, and increasing the size of orchards through land acquisition (renting or purchasing) facilitates the use of shade cloth. The most significant barriers to the adoption of this technology are rising costs for shade cloth, labor, and fertilizers. In contrast, lower prices encourage the acquisition of this technology. The positive relationship between temperature and adoption rate of this technology suggests that apple growers should protect their crops from the effects of rising temperatures.

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