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Title

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Permalink

<https://escholarship.org/uc/item/3tp1r1cb>

Journal

California Agriculture, 79(3-4)

ISSN

0008-0845

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Publication Date

2025

DOI

10.3733/001c.155765

Supplemental Material

<https://escholarship.org/uc/item/3tp1r1cb#supplemental>

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For California walnut drying, fuel choice and improved training and automation may reduce energy consumption

Training, switching fuel type, and increased automation are feasible approaches to reduce energy consumption in walnut drying.

by Alice Dien, Lucía Félix-Palomares, Shira Bergman, Kurt Kornbluth, David C. Slaughter and Irwin R. Donis-González

Online: <https://doi.org/10.3733/001c.155765>

California is the leading walnut producer in the United States, producing 752,000 short tons of in-shell walnuts in 2022, which makes up nearly half of the world's walnut exports (USDA 2022, 2023). California's main walnut-growing counties include San Joaquín, Butte, Tulare, Sutter, and Stanislaus, each harvesting over 50,000 short tons of in-shell walnuts annually (USDA 2020).

From August through November, walnuts are harvested and transported to one of California's 400 walnut hulling and drying facilities (DFA of California 2002). These facilities remove the walnut hulls, leaving the kernel inside the shell, to produce in-shell walnuts. The walnuts are then cleaned, sorted, and dried to an 8% wet basis moisture content (MC_{wb}) to preserve quality, ensure safety, and maintain profitability (Khair and Pan 2019; Thompson and Grant 1992).

Abstract

Drying is an energy-intensive step in walnut production, accounting for 19% of processing costs and contributing to greenhouse gas emissions. This study surveyed 19 California walnut drying facilities to update energy consumption estimates and identify factors influencing energy use. The variables analyzed included production volume, implementation of energy conservation strategies, the type of fuel used for drying, and ambient air conditions (temperature and relative humidity). The results show that the average energy consumption for walnut drying in California was 1.156 million British thermal units per short ton of in-shell dried walnuts, 11.1% lower than 2009 estimates. Natural gas facilities used 41.5% less energy than those using propane. The type of fuel used for drying was the only factor that significantly affected energy consumption; energy conservation strategies, including in-bin moisture meters and air recirculation, did not have a significant impact. This suggests the need for improved application of energy conservation strategies through better automation and operator training.

A fan room at an industrial-scale walnut processing and drying facility, with five centrifugal drying fans in the background, each measuring about 10 feet in height. Drying is one of the most energy-intensive and expensive steps in walnut production. From left to right: Dr. Irwin R. Donis-González, Chris Fedora (Fedora Farms, Meridian, Calif.), Ph.D. Candidate Alice Dien, and Bailey, the Fedora Farms dog. Photo: A. Dien and I.R. Donis-González.



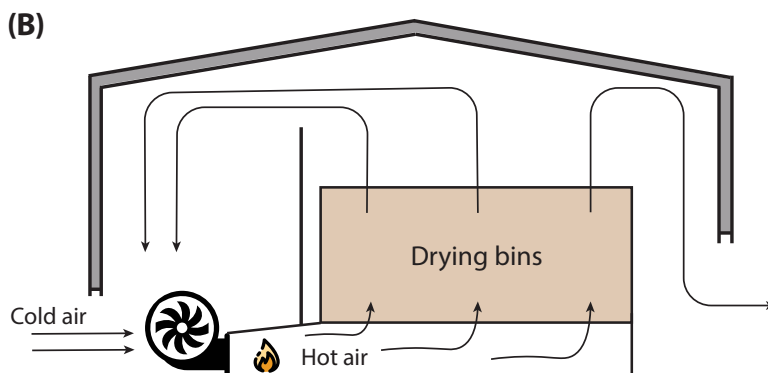


FIG. 1. (A) A California walnut drying facility with stationary bin dehydrators. (B) Stationary bin dehydrator schematic; arrows show the flow of air.

Walnuts are mostly dried in stationary bin dehydrators (fig. 1A), which can handle between 30 and 133 tons each (Klonsky et al. 2009). Fans introduce outside air into the facility at 20 to 30 cubic feet per minute (cfm) per cubic foot (ft³) of in-shell walnuts. The air is then heated to about 110°F by burning natural gas (NG) or propane. The drying process lasts between 24 and 48 hours, depending on ambient air conditions and the initial MC_{wb}, which can range from 13% to 40% (Khir et al. 2013; Thompson et al. 1997).

Energy cost in walnut drying

Drying is one of the most energy-intensive and expensive steps in walnut production, accounting for nearly 19% of total processing costs (Grant et al. 2013). Energy is a prominent concern in California agriculture, with government policies pushing for reduced fossil fuel use, and rising fuel costs decreasing processing margins. Therefore, reducing energy use in the drying operation helps the California walnut industry achieve its economic and environmental goals.

The fuel used for drying contributes most of the energy cost of drying in-shell walnuts, with electricity to run the operating fans and conveyor belts accounting for a much smaller fraction. Energy usage estimates

for walnut drying have not been updated since 2009 (Klonsky et al. 2009). Thus, this study aims to provide updated estimates and identify strategies to reduce energy use, thereby lowering greenhouse gas emissions and operating costs.

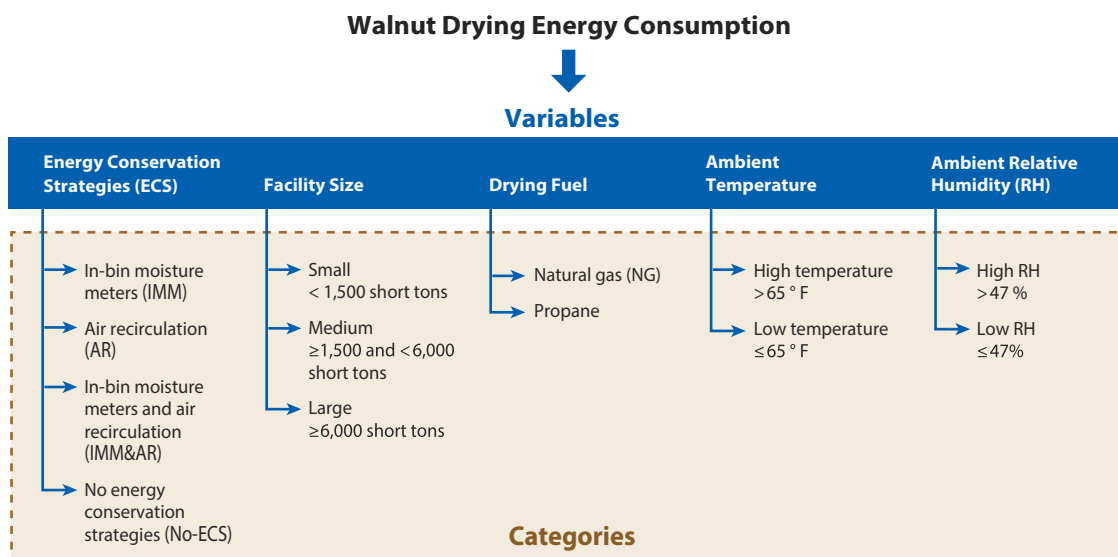
Factors influencing energy use

Several methods have been explored to reduce energy use, including two-stage or step-down temperature drying (Chen et al. 2020) and infrared drying (Dolgun et al. 2021). However, high capital costs and difficulty in application hinder their adoption. Our study focuses on five existing variables in walnut drying facilities (fig. 2) and their impact on energy consumption, as described below.

Energy conservation strategies

Energy conservation strategies (ECS) are cost-effective methods that can theoretically lead to energy savings. These methods include in-bin moisture meters (IMMs) to monitor MC_{wb}; air recirculation (AR); air velocity optimization; correct installment and adjustment of the fan burner; reduction of dryer operation during cold, moist mornings; and shallower bins (Rumsey et al. 1981; Rumsey and Thompson 1994; Thompson et al.

FIG. 2. Studied variables (blue box) and categories (brown box) that could influence walnut drying energy consumption.



1997). Previous studies suggest that the highest energy savings, ranging from 30% to 50%, are achieved with IMMs, followed by 20% to 40% with AR (Rumsey et al. 1981; Thompson et al. 1997). Consequently, our study focuses on these two ECS.

IMMs are pairs of steel plates permanently mounted inside drying bins that measure the electrical resistance of walnuts and relate it to their MC_{wb}. Without IMMs, operators gauge drying completion by sampling top walnuts. This is an inaccurate method given that walnuts on top dry more slowly than those lower in the bin. This often results in over-drying, which affects walnut quality, reduces revenue, and increases energy consumption due to extended drying time (Thompson et al. 1997).

AR can reduce energy consumption by recirculating warm air within the dryer, rather than constantly introducing new air, thereby reducing the energy required to heat the air to 110°F. Dryers inside a building recirculate air through a passage connecting the drying and fan rooms (fig. 1B). This recirculation is adjusted by opening or closing doors and vents that connect the building to the outside (Thompson et al. 1997).

Size of facilities

Larger facilities may benefit from economies of scale by having more sophisticated drying equipment (IMMs, automated AR) and operating closer to their maximum capacity. As a result, less energy is required to maintain optimal drying conditions, reducing per-unit energy

costs and improving overall process efficiency. Facility size, based on production volume, varies widely in California. A previous survey of 11 walnut hulling and drying facilities reported annual drying throughputs ranging from 79 to 8,838 short tons of hulled in-shell dried walnuts (Klonsky et al. 2009).

Surveyed facilities reported seasonal throughputs ranging from 150 to 46,000 short tons of in-shell dried walnuts. The average seasonal production was 6,706 short tons per season, substantially higher than the 1,883 short tons reported in a previous study (Klonsky et al. 2009). However, the throughput between the first and second largest facilities differed considerably, ranging from 46,000 to 11,000 tons, as shown in table 1.

Choice of fuel used for drying

Facilities using NG experience a 52% decrease in drying costs compared to those using propane (Klonsky et al. 2009). NG is supplied through pipelines in its gaseous state, while propane is distributed as a liquid in portable tanks or delivered to a permanent on-site tank. NG delivers 1,035 British thermal units (Btu) per cubic foot (ft³) of energy density (higher heating value or HHV), compared to 2,500 Btu for propane (Bartok 2004; EIA 2024). However, NG remains more cost-effective despite propane’s higher energy density. In California, for example, industrial NG cost an average of 13.3 USD per million Btu (MMBtu) in 2022, whereas wholesale propane cost 16.8 USD per MMBtu (EIA 2022a, 2022b).

TABLE 1. Original raw survey data, including ECS, drying fuel type, walnut production, fuel and electricity consumption, and calculated drying cost

Facility	Energy conservation strategies (ECS)	Drying fuel	Walnut production, short tons of in-shell walnuts (< 8% MC _{wb})	Fuel use in drying season (MMBtu)	Electricity use in drying season (MMBtu)	Calculated drying cost (USD/ton)
1	No-ECS	NG	576	824.72	54.61	23.81
2	No-ECS	NG	4,018	3,892.13	257.74	16.12
3	IMM	NG	5,180	4,210.48	278.82	13.52
4	IMM	NG	4,593	4,328.77	286.65	15.67
5	IMM&AR	Propane	7,500	12,446.56	824.21	33.56
6	IMM&AR	NG	5,000	7,583.87	502.20	25.22
7	No-ECS	Propane	3,185	2,074.43	137.37	13.17
8	No-ECS	Propane	445	483.76	32.03	21.98
9	No-ECS	Propane	150	549.45	36.38	74.07
10	IMM	NG & propane	6,000	21,132.49	1,399.39	66.85
11	IMM	NG	46,000	30,957.91	2,050.02	11.19
12	IMM	NG	2,520	3,065.24	202.98	20.23
13	IMM	NG	11,000	10,224.18	677.04	15.46
14	IMM&AR	Propane	9,000	10,952.97	725.30	24.61
15	IMM&AR	NG	3,000	2,464.42	163.19	13.66
16	IMM&AR	Propane	10,000	8,214.73	543.98	16.61
17	IMM&AR	NG	5,660	7,832.08	518.64	23.01
18	AR	Propane	932	1,744.48	115.52	37.84
19	IMM&AR	Propane	2,646	5,094.81	337.38	38.93

Air temperature and humidity

Drying efficiency depends on ambient air conditions, primarily temperature and relative humidity (RH) (Kudra 2004). Lower temperatures and higher RH, potentially due to rainfall, require more energy to reach desired drying conditions (110°F, ~ 15% RH).

Facilities in nine counties

This study surveyed 19 industrial-scale hulling and drying facilities from nine counties, with an average seasonal production of over 1,100 short tons of in-shell walnuts (fig. 3). These facilities represented nearly 5% of California's drying facilities and 18.8% of the 676,000 short tons California produced in 2018 (USDA 2019). The selection criteria included availability and willingness to participate; however, not all participants answered all questions.

Data were provided by a walnut huller and dryer owner, manager, or technician through in-person interviews, a review of historical records, and a remote survey (online technical appendix 1). Key variables included seasonal throughput in short tons of in-shell dried walnuts, the number of ECS used, and consumption of drying fuel and electricity. To gauge cost-saving

practices, respondents were asked about solar power installations in their facilities.

Facilities were classified as small (< 1,500 short tons/season), medium (≥ 1,500 and < 6,000 short tons/season), and large (≥ 6,000 short tons/season). The ranges were determined to ensure a representative sample of facilities in each category.

We retrieved daily average temperature and RH from the National Oceanic and Atmospheric Administration (NOAA) database for the 2018 drying season from August through November (NOAA n.d.). Environmental conditions across counties ranged from 60°F to 75°F and 31% to 63% RH. Accordingly, the surveyed facilities were categorized into low-temperature (≤ 65°F) and high-temperature (> 65°F) groups, and low-RH (≤ 47%) and high-RH (> 47%) groups.

Energy and cost calculations

Fuel usage was reported in therms for NG or gallons for propane. Electricity use was often unavailable or reported only as total kilowatt-hours (kWh) from utility bills, overestimating consumption by including non-drying equipment. Therefore, the *facility energy consumption* (FEC_i) was calculated using Equation 1, where fuel contributed 93.8% to the drying energy, and electricity was estimated to be an additional 6.2% (Klonsky et al. 2009). All energy values were converted to MMBtu using the conversion factors in table A1 (online technical appendix 1).

$$FEC_i = \frac{100}{93.8} (NG_i + P_i) = 1.066 (NG_i + P_i) \quad (1)$$

where *i* is the facility (from 1 to 19), and NG_i and P_i are the reported NG and propane consumption in MMBtu for facility *i*.

Based on the results from the individual facilities, we are interested in the *California average energy consumption* (CEC_T) that was used to achieve a dryness level of 8% MC_{wb} per short ton. This was calculated using Equation 2, based on all surveyed facilities.

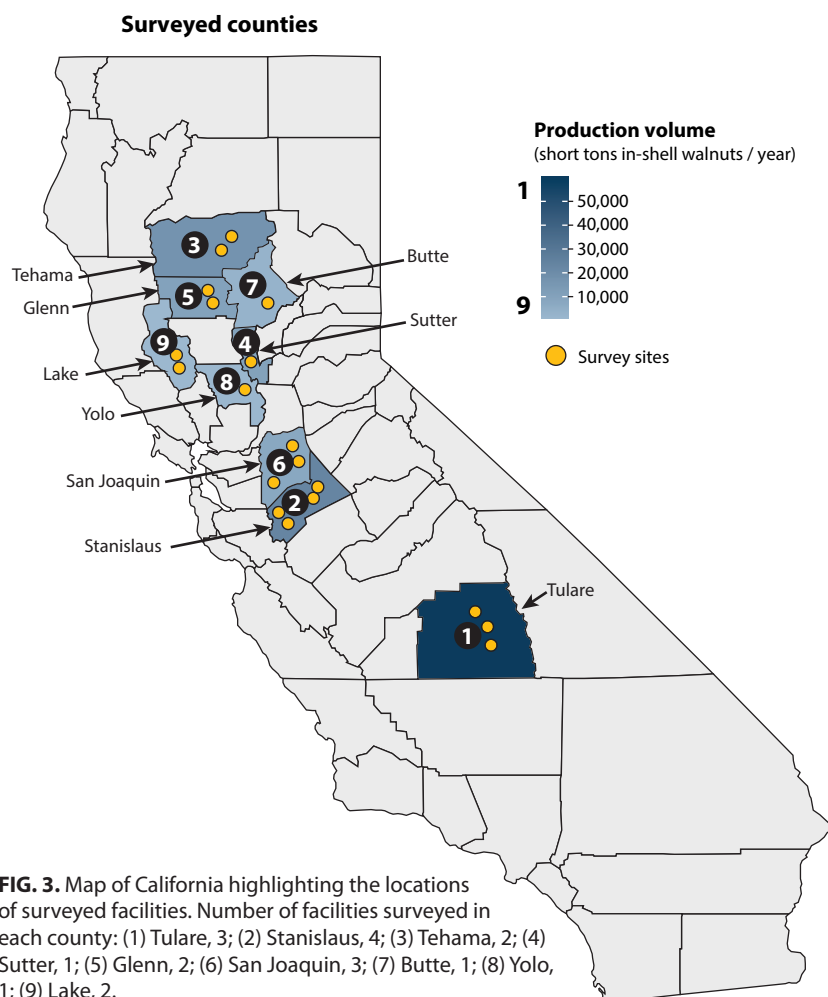
$$CEC_T = \frac{\sum_{i=1}^{19} FEC_i}{\sum_{i=1}^{19} T_i} \quad (2)$$

where FEC_i is the facility energy consumption in MMBtu, and T_i is the facility throughput in short tons of in-shell dried walnuts.

Then, to facilitate comparisons between facilities, we calculated a standardized facility energy consumption (SFEC_i) by dividing each facility's FEC_i by its seasonal throughput, T_i, as shown in Equation 3.

$$SFEC_i = \frac{FEC_i}{T_i} \quad (3)$$

where FEC_i is the total facility energy consumption in MMBtu, and T_i is the facility throughput in short tons of in-shell dried walnuts (< 8% MC_{wb}).



We then categorized facilities based on the factors that influence energy consumption for drying (fig. 2). The result is the *average standardized category energy consumption* ($ASEC_x$), which will allow us to identify the characteristics of a facility that influence its energy consumption (Equation 4).

$$ASEC_x = \frac{\sum_{i=m}^n SFEC_i}{n} \tag{4}$$

where m refers to the first facility counted in category x, and n refers to the number of facilities in that category.

Last, drying costs were calculated based on the amount of fuel and electricity required to dry one short ton of in-shell dried walnuts. Electricity costs were based on annual averages of California utility rates (EIA 2022a, 2022b).

Statistical methods

Data were analyzed using R (R Foundation for Statistical Computing, Vienna, Austria). Significant differences between $ASEC_x$ were tested using ANOVA for variables with three or more categories, or a t-test for variables with two categories.

A stepwise linear regression was used to identify the significant predictors of $SFEC_i$. Independent variables (categories in fig. 2) were coded as binary (Brook and Arnold 1985). The model is expressed in Equation 5.

$$SFEC_i = \beta_0 + \beta_{IMM}X_{IMM} + \beta_{AR}X_{AR} + \beta_{IMM\&AR}X_{IMM\&AR} + \beta_{Small}X_{Small} + \beta_{Large}X_{Large} + \beta_{Fuel}X_{Fuel} + \beta_{Temp}X_{Temp} + \beta_{RH}X_{RH} \tag{5}$$

The final model's R^2 and statistical power were calculated to assess model reliability (Myors and Murphy 2023). We used a 90% confidence level due to a small sample size (Labovitz 1968). Additionally, the sample size for future surveys was determined based on 80% and 90% statistical power (Peterman 1990).

Energy use lower since 2009

The statewide average energy consumption (CEC_T) was 1.156 MMBtu per short ton of in-shell dried walnuts, 11.1% lower than previously reported (Klonsky



Exterior view of the Fedora Farms, Inc., walnut processing and drying facility. The building contains hulling, cleaning, and material-handling equipment used to prepare walnuts for in-bin drying. The doors along the lateral side are opened during the drying season to intake outdoor air. Photo: A. Dien and I.R. Donis-González.

et al. 2009). The following sections discuss these changing patterns.

Moisture meters in common use

Most facilities in our survey have adopted some energy conservation strategies (ECS), with in-bin moisture meters the most popular. As shown in figure 4A, only 26% of surveyed facilities did not use any ECS (No-ECS, $n = 5$). Of the remaining 74%, some employed in-bin moisture meters (IMM, $n = 6$), air recirculation (AR, $n = 1$), or a combination of both (IMM + AR, $n = 7$). Among the 14 facilities using ECS, 93% used IMM, whereas only 57% applied AR.

While facilities using both moisture meters and air recirculation achieved the greatest energy reductions, with moisture meters playing the most important role, these results are not statistically significant. Figure 5A shows the $SFEC_i$ distributions and $ASEC_x$ values based on ECS adoption. On average, IMM+AR facilities showed the highest $ASEC_x$ reduction of 14.5% compared to No-ECS facilities. Similarly, IMM-only facilities showed a 13.3% energy reduction. The difference in energy consumption between IMM+AR and IMM-only facilities was only 1.4%. These reductions fell short of the 30% to 50% reductions reported in pre-2009 studies (Rumsey et al. 1981; Thompson et al. 1997).

Natural gas may be more energy-efficient than propane for drying walnuts, but our study can't determine whether this result will vary based on the characteristics of different facilities.

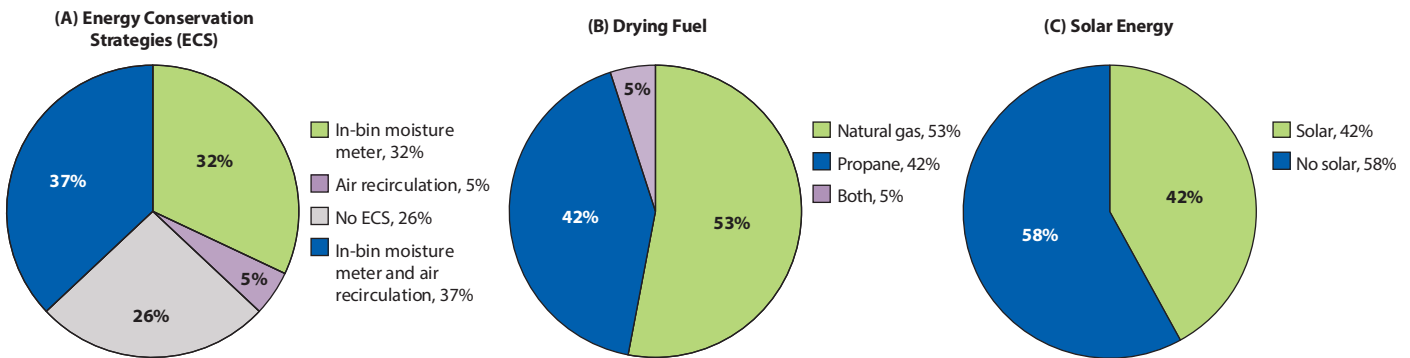
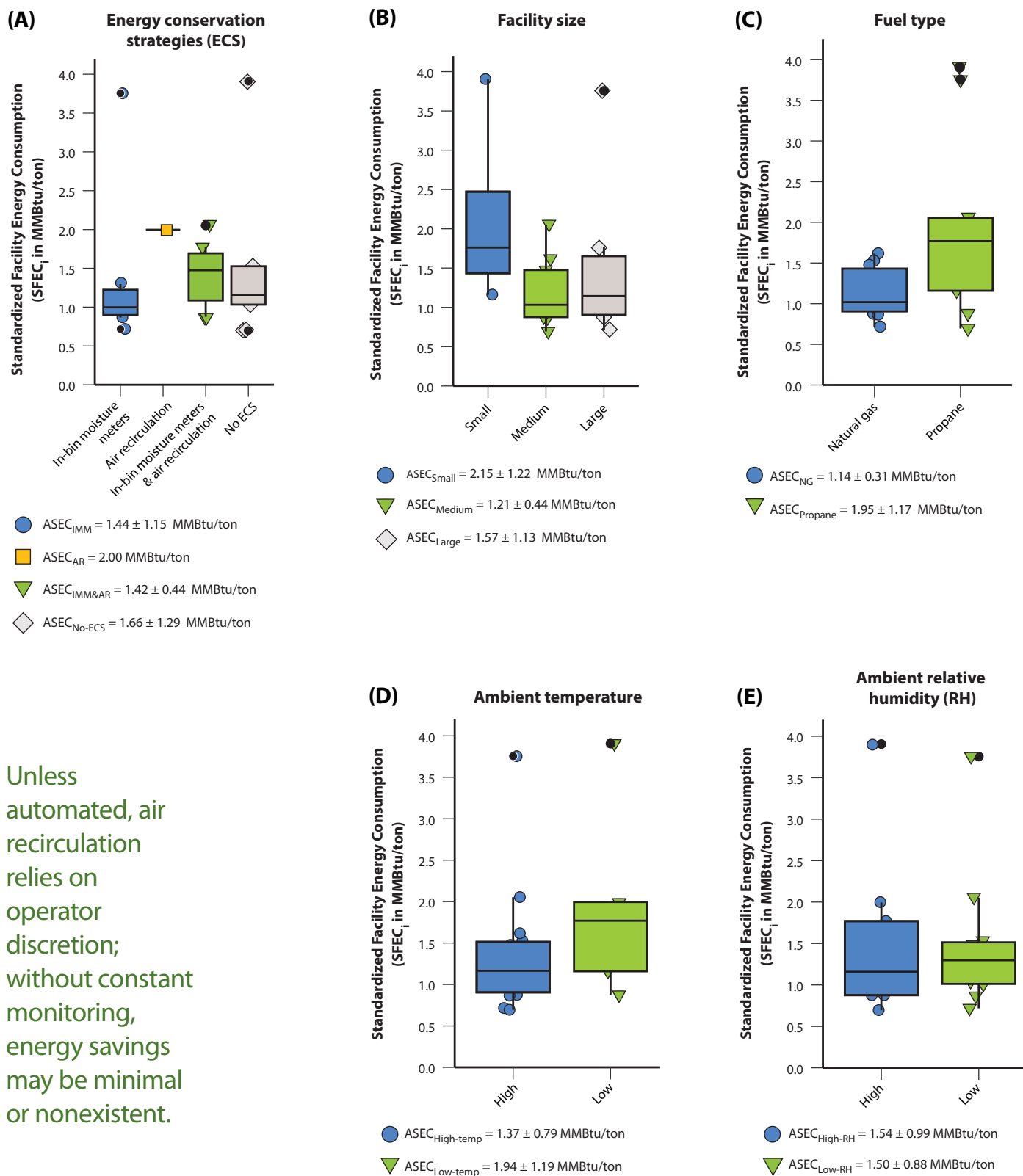


FIG. 4. Percentage of users of (A) energy conservation strategies, (B) type of drying fuel, and (C) solar energy.



Unless automated, air recirculation relies on operator discretion; without constant monitoring, energy savings may be minimal or nonexistent.

FIG. 5. Boxplots showing the standardized facility energy consumption (SFEC_i) and average standardized category energy consumption (ASEC_x) in MMBtu per short ton of in-shell dried walnuts for (A) ECS, (B) facility size, (C) fuel type, (D) temperature, and (E) relative humidity. The edges of the boxes represent the 25th and 75th percentiles, and the line inside the box represents the median.

Questions about recirculation

As noted above, the use of AR in addition to IMM improved energy efficiency by only 1.4%, suggesting that AR played a minor role. Along similar lines, the facility that used only AR had the highest energy usage in terms of $ASEC_x$. However, statistical analysis showed no significant differences in $ASEC_x$ across ECS categories (ANOVA, P -value = 0.928).

Possible explanations for lower-than-expected energy savings in ECS facilities include inadequate AR application, alternative energy conservation strategies used by No-ECS facilities (such as turning off dryers at night), or variations in final MC_{wb} between facilities.

For example, AR is recommended when indoor temperatures are at least 10°F to 15°F higher than outside, with up to 60% of drying air recirculated (Thompson et al. 1997). In practice, AR should be minimized during hot afternoons and maximized during cooler evenings, nights, and early mornings. However, unless automated, AR relies on operator discretion; without constant monitoring, energy savings may be minimal or nonexistent (Rumsey et al. 1981).

Additionally, operators may intentionally over-dry walnuts to avoid batch rejection due to a few high-moisture nuts ($> 8\% MC_{wb}$). A study showed that reducing moisture from 8% to 6% MC_{wb} added six hours to the drying process, significantly increasing time and energy consumption (Thompson and Grant 1992). However, because our study did not collect moisture data, we were unable to compare MC_{wb} across facilities.

Economies of scale

As shown in figure 5B, small facilities had the highest $ASEC_x$, exceeding medium and large facilities by 77.7% and 37%, respectively. However, statistical analysis showed no significant differences in $ASEC_x$ based on facility size (ANOVA, P -value = 0.239).

Our observations during the study suggest that larger facilities often have more advanced infrastructure, which may explain their lower $SFEC_i$. For example, larger facilities tend to use controllers and sensors to regulate fans, burners, and AR automatically, and often have IMM permanently installed.

Natural gas may use less energy

NG may be more energy efficient than propane for drying walnuts, but our study can't determine whether this result will vary based on the characteristics of different facilities. This will require additional surveys to confirm.

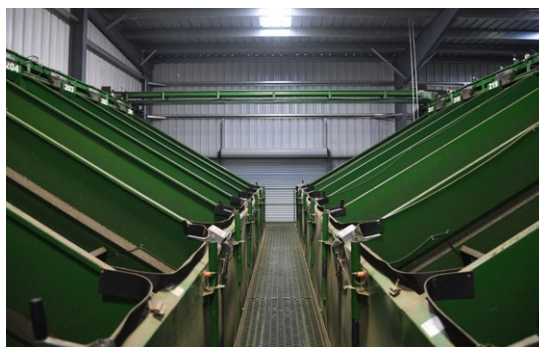
Natural gas is used as a drying fuel by 53% of facilities, with 42% using propane and 5% using both NG and propane (fig. 4B). In contrast, Klonsky et al. (2009) found that 45% of facilities used NG and 54% used propane. This discrepancy may be due to differences in the sampled populations, facility sizes, and increased access and lower cost of NG.

Figure 5C shows $ASEC_x$ (energy consumption averaged across facilities within the same category) and

$SFEC_i$ distributions (not averaged) by drying fuel type. NG facilities had 41.5% lower $ASEC_x$ than propane facilities and less variability in $SFEC_i$. However, statistical analysis (t-test) showed no significant differences in $ASEC_x$ based on fuel type (P -value = 0.076).



Two empty walnut drying bins with in-bin moisture meters (IMM) installed at the center of each bin. The perforated bin floor is visible, supporting uniform vertical airflow through the walnuts during drying. Photo: I.R. Donis-González.



Central walkway between two rows of in-bin walnut dryers at Fedora Farms. The image shows the layout of the drying bins, their numbering system, and the structure supporting air distribution and monitoring equipment. Photo: Alice Dien.



Rear fan room of the in-bin walnut drying facility, where the centrifugal fans and burner assemblies provide heated air to the drying bins. The angled green bin tops (burners) connect to individual ducts leading to each blower. Roll-up doors along the back wall control outdoor air intake and serve as the main mechanism for air recirculation (AR) during drying. Photo: Alice Dien.

Although vaporizing burners used for propane are about 5% less efficient than gas burners, this alone does not account for the $ASEC_x$ difference observed in this study. A possible explanation is improper primary oxygen adjustment, which produces a yellow flame and results in higher energy loss compared to a blue flame. Future work should explore this issue further and educate propane users on optimizing burner performance.

The drying fuel type was the only variable significantly correlated with $SFEC_i$ (P -value < 0.1) (fig. 2). The final model is given by Equation 6.

$$SFEC_i = 1.945 - 0.805 X_{fuel} \quad (6)$$

where $X_{fuel} = 1$ represents the use of NG. The model indicates that facilities using NG consume 0.805 MMBtu less energy per ton of in-shell dried walnuts compared to those using propane. However, the low coefficient of determination ($R^2 = 0.21$) suggests that, while drying fuel is an important variable, other variables not included in this analysis may also influence $SFEC_i$. Therefore, this model is not suitable for predicting energy use in California walnut facilities (Montgomery et al. 2021).

Additionally, the statistical power for the final model was 25.3%, which is well below the threshold desired for statistical studies (Kraemer and Blasey 2015). To achieve 80% and 90% statistical power in a stepwise linear regression model, surveys would need to include 89 and 122 facilities, respectively (Peterman 1990).

Ambient conditions

As expected, facilities in the high-temperature, low-RH range had lower $ASEC_x$ than those in the low-temperature, high-RH range (figs. 5D and 5E), with temperature having a greater impact on $SFEC_i$ than RH. These results are consistent with the understanding that lower temperatures require more energy to reach the target drying temperature of 110°F.

However, statistical analysis (t-test) found no significant differences in $ASEC_x$ based on temperature or RH (P -value = 0.362 and 0.956, respectively). These results suggest that, while temperature and RH affect

drying, other factors likely play a more significant role in energy consumption.

Nut prices and drying costs

On average, drying costs were lower at larger and medium-sized facilities (28.1 and 19.9 USD per ton of in-shell dried walnuts, respectively) compared to small facilities (39.3 USD per ton). This cost reduction is likely due to economies of scale, where increased production leads to lower per-unit costs. Facilities using propane had higher drying costs (32.6 USD per ton) than those using natural gas (17.8 USD per ton), representing a 45.4% reduction, consistent with findings from Klonsky et al. (2009).

While energy prices have increased, walnut prices peaked in 2014 before dropping due to supply-demand imbalances. This price decline, coupled with rising energy and irrigation costs, has put significant financial pressure on walnut growers and handlers (Northcutt 2015). We retrieved historical data from the USDA to track how walnut prices have changed over the past 20 years (CASS 1997; CDFA 2017, 2023; USDA 2005). Figure 6 shows California's rising walnut drying energy costs and fluctuating producer prices since 1992.

In response to rising energy costs, 42% of survey participants reported using solar energy (fig. 4C) for part of their electricity generation. This shift is driven by regulatory changes, fluctuations in fuel prices, and the economic benefits of net metering, which credits facilities for excess electricity that they send to the grid (National Academies of Sciences, Engineering, and Medicine 2023).

Future potential to explore

Energy use to dry a short ton of in-shell walnuts has decreased by 11.1% since previous estimates (Klonsky et al. 2009). However, while in-bin moisture monitoring and air recirculation show potential for further reducing energy consumption, their impact in this study

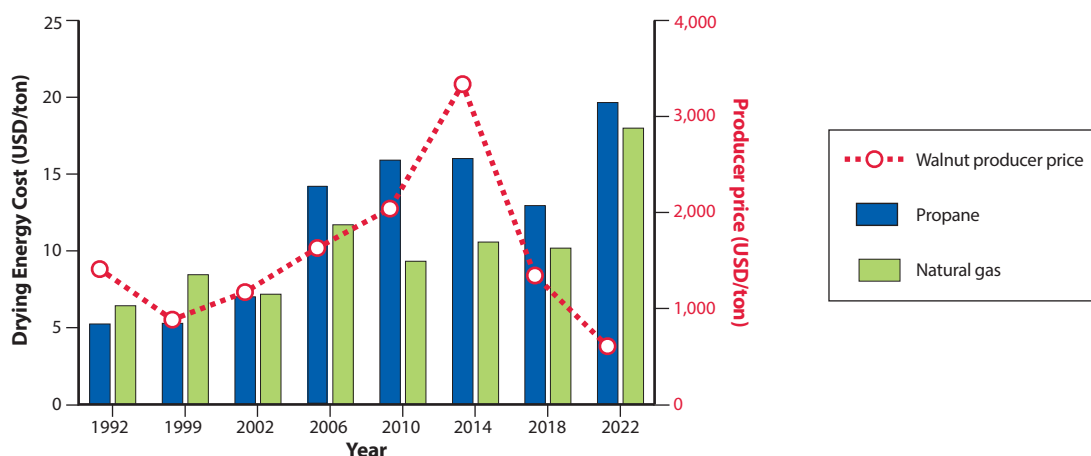


FIG. 6. Average drying cost and producer price (in-shell, dried) evolution in California between 1992 and 2022.

was less than expected, and this impact cannot be separated from other variables. Similarly, natural gas may be a more efficient drying fuel than propane, but it is possible that this result was influenced by other characteristics of drying facilities.

To maximize energy savings, walnut drying facilities should invest in more effective and automated systems, such as advanced controllers and sensors, to support consistent process control and reduce reliance on manual adjustments. This is especially critical for air recirculation, which requires precise and responsive management to be effective. Continued operator training, combined with closer collaboration between researchers, technology providers, and drying facility staff, is essential to ensuring that energy conservation strategies are implemented and applied consistently over time.

Future studies should investigate the moisture content (MC_{wb}) targets set by walnut dryer operators and the actual values measured, as this could help identify facilities that consistently over-dry walnuts.

Excessive drying leads to longer drying times and increased energy use, and could be a significant variable to include in a study.

The limitations of the current study, particularly the small sample size, highlight the need for broader surveys. Increasing the number of facilities to at least 89 would improve the statistical power and enable more robust conclusions about the factors that influence energy consumption in walnut drying. 

A. Dien and L. Félix-Palomares contributed equally to this work. A. Dien is Ph.D. Candidate, L. Félix-Palomares is MSc, S. Bergman is MSc, K. Kornbluth is Adjunct Professor, D.C. Slaughter is Professor, and I. Donis-González is Associate Professor, Department of Biological and Agricultural Engineering, UC Davis.

We thank the University of California, Agriculture and Natural Resources (UC ANR), and the California Walnut Board and Commission for their support of this research. We also thank all survey participants and Chris Fedora of Fedora Farms Inc. for generously providing access to the facility to take photographs.

References

- Bartok JW. 2004. Approximate Heating Value of Common Fuels. University of Connecticut. <https://ipm.cahnr.uconn.edu/heating-value-fuels/>
- Brook RJ, Arnold GC. 1985. *Applied Regression Analysis and Experimental Design*. Boca Raton: Taylor and Francis Group. 256 p. <https://doi.org/10.1201/9781315137674>
- [CASS] California Agricultural Statistics Service. 1997. Walnut, Raisin, & Prune Report State Summary – 1996 Crop Year. www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Handler_Reports/199810wrrp.pdf
- [CDFA] California Department of Food and Agriculture. 2017. Walnut/Raisin/Prune Report State Summary – 2016 Crop Year. USDA National Agricultural Statistics Service. www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Walnut/Objective-Measurement/201710wrrp_updated.pdf
- CDFA. 2023. Walnut/Raisin/Prune Report State Summary – 2022 Crop Year. USDA National Agricultural Statistics Service. www.nass.usda.gov/statistics_by_state/California/Publications/Specialty_and_Other_Releases/Handler_Reports/2022wrrp_1023.pdf
- Chang C, Venkitasamy C, Zhang W, et al. 2020. Effect of step-down temperature drying on energy consumption and product quality of walnuts. *J Food Eng* 285:110105. <https://doi.org/10.1016/j.jfoodeng.2020.110105>
- DFA of California. 2002. Walnut Huller & Dryer. Food Safety & GMP Manual. https://dfaof-california.com/wp-content/uploads/walnut_huller_dryer_inspection.pdf
- Dolgun G, Aktaş M, Dolgun EC. 2021. Infrared convective drying of walnut with energy-exergy perspective. *J Food Eng* 306:1–11. <https://doi.org/10.1016/j.jfoodeng.2021.110638>
- [EIA] U.S. Energy Information Administration. 2020. Units and calculators explained. British thermal units. www.eia.gov/energyexplained/units-and-calculators/british-thermal-units.php (accessed December 2025).
- EIA. 2022a. Natural gas. California natural gas industrial price. www.eia.gov/dnav/ng/hist/n3035ca3m.htm (accessed December 2025).
- EIA. 2022b. Petroleum & other liquids. U.S. propane wholesale/retail price by refiners www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMA_EPLLPAPWG_NUS_DPG&f=M (accessed December 2025).
- EIA. 2024. Natural gas monthly. www.eia.gov/naturalgas/monthly/ (accessed January 2024).
- Grant JA, Caprile JL, Doll DA, et al. 2013. Sample Costs to Establish a Walnut Orchard and Produce Walnuts. University of California Cooperative Extension. https://coststudyfiles.ucdavis.edu/uploads/cs_public/6d/d5/6dd51838-68ce-4294-83a5-1eeb460baeda/walnutvn2013.pdf
- Khair R, Pan Z. 2019. Chapter 16: Walnuts. In *Integrated Processing Technologies for Food and Agricultural By-Products*. Pan Z, Zhang R, Zicari S (eds.). Elsevier Academic Press. p 391–411. <https://doi.org/10.1016/B978-0-12-814138-0.00016-2>
- Khair R, Pan Z, Atungulu GG, et al. 2013. Size and moisture distribution characteristics of walnuts and their components. *Food Bioprocess Tech* 6(3):771–82. <https://doi.org/10.1007/s11947-011-0717-1>
- Klonsky K, Thompson J, Grant J, et al. 2009. Sample Costs to Hull and Dry Walnuts. University of California Cooperative Extension. <https://ucanr.edu/sites/glenn/files/185671.pdf>
- Kraemer HC, Blasey C. 2015. *How Many Subjects? Statistical Power Analysis in Research*. London: Sage Publications. <https://doi.org/10.4135/9781483398761>
- Kudra T. 2004. Energy aspects in drying. *Dry Technol* 22(5):917–32. <https://doi.org/10.1081/DRT-120038572>
- Labovitz S. 1968. Criteria for selecting a significance level: A note on the sacredness of .05. *Am Sociol* 3(3):220–2. www.jstor.org/stable/27701367
- Montgomery DC, Peck EA, Vining GG. 2021. *Introduction to Linear Regression Analysis, 6th Edition*. John Wiley & Sons. www.wiley.com/en-us/Introduction+to+Linear+Regression+Analysis%2C+6th+Edition-p-9781119578727
- Myors B, Murphy KR. 2023. *Statistical Power Analysis: A Simple and General Model for Traditional and Modern Hypothesis Tests*. New York: Routledge. 224 p. <https://doi.org/10.4324/9781003296225>
- National Academies of Sciences, Engineering, and Medicine. 2023. *The Role of Net Metering in the Evolving Electricity System. Chapter 4: Economic Considerations Related to Net Metering*. Washington, DC: The National Academies Press. www.nationalacademies.org/projects/DEPS-BEES-21-01/about
- [NOAA] National Oceanic and Atmospheric Administration (n.d.). Graphical forecasts - Northern California. National Weather Service. <https://graphical.weather.gov/sectors/northcalifornia.php> (accessed December 2018).
- Northcutt G. 2015. California walnut market takes an unexpected hit from several sides. Farm Progress Reports. www.farmprogress.com/tree-nuts/california-walnut-market-takes-an-unexpected-hit-from-several-sides
- Peterman RM. 1990. Statistical power analysis can improve fisheries research and management. *Can J Fish Aquat Sci* 47(1):2–15. <https://doi.org/10.1139/f90-001>
- Rumsey T, Thompson J. 1993. Drying and Energy Efficiency of a New Type of Commercial Walnut Dryer. UC Davis Dept. of Plant Sciences, UC ANR. <https://ucdavis.app.box.com/s/ass-4ftqzaecpquoczd4lyz574lliwq>
- Rumsey T, Thompson J, Young J. 1981. Walnut Drying. California Walnut Board. Walnut Research Reports 1981. Thompson J, Grant J. 1992. New moisture meter could curb overdrying of walnuts. *Calif Agr* 46(2):31–4. <https://californiaagriculture.org/article/110339-new-moisture-meter-could-curb-overdrying-of-walnuts>
- Thompson J, Rumsey TR, Grant JA. 1997. Dehydration. In *Walnut Production Manual*. Ramos DD (ed.). UC ANR. p 277–84. <https://ucanr.edu/sites/kingscounty/files/19005.pdf>
- [USDA] United States Department of Agriculture. 2005. Walnut/Raisin/Prune Report State Summary – 2005 Crop Year. National Agricultural Statistics Service. https://data.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Handler_Reports/200610wrrp.pdf
- USDA. 2019. 2019 California Walnut Objective Measurement Report. USDA National Agricultural Statistics Service. www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Walnut/Objective-Measurement/201908walom.pdf
- USDA. 2020. 2019 California Walnut Acreage Report. USDA National Agricultural Statistics Service. www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Walnut/Acreage/2020walac.pdf
- USDA. 2022. Tree Nuts: World Markets and Trade. USDA Foreign Agricultural Service. https://agfstorage.blob.core.windows.net/misc/FP_com/2022/02/18/Ata.pdf
- USDA. 2023. 2023 California Walnut Objective Measurement Report. USDA National Agricultural Statistics Service. www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Walnut/Objective-Measurement/202309walom.pdf