

Article

Integrated Differential Diagnosis Applied to Pecan Kernels: Nutritional Standards on a Defatted Basis and Correction Factors for Lipid Extraction

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Highlights

What are the main findings?

- Defatting pecan kernels with hexane significantly concentrated N, P, K, Mg, Fe, Mn, and Zn, reduced Ca and Na, and did not affect Cu.
- Correction factors were developed to convert nutrient concentrations from a defatted basis to a non-defatted basis, enabling valid comparisons with the existing literature.
- Integrated Differential Diagnosis (IDD) nutritional standards were established and successfully validated, detecting site-specific deficiencies (P, Mn, Cu) and excess (Na) consistent with soil conditions.

What are the implications of the main findings?

- These standards and correction factors provide a reliable diagnostic tool for nutritional management in pecan orchards, particularly in the Aldama region, Mexico.
- The methodology can be adapted to other crops and regions, supporting more accurate nutritional interpretation and improved fertilization strategies.

Abstract

This research addressed the lack of standardization in the nutritional interpretation of pecan kernels. The objective was to evaluate the effect of kernel defatting on nutrient concentration, generate correction factors for each element, and establish nutritional standards through the Integrated Differential Diagnosis (IDD). For this purpose, 222 kernel samples of the Western Schley variety were analyzed, collected at the “El Eden” orchard from 2023 to 2025 in Aldama, Chihuahua, Mexico. In these samples, the concentration of macro and micronutrients was determined on a defatted basis and compared with their non-defatted equivalent using a comparison of sample means by paired observations. From this, correction factors were calculated, and subsequently, nutritional standards were generated, which were validated internally and externally in an orchard with similar conditions. The results revealed that defatting significantly increased the concentrations of N, P, K, Mg, Fe, Mn, and Zn, while Ca and Na showed a significant decrease, and Cu showed no changes in its concentration. The correction factors allowed the transformation of concentrations from the defatted basis to the non-defatted basis, facilitating comparison with previously reported literature. The validation of the standards indicated that they were useful for detecting nutritional imbalances consistent with soil characteristics, highlighting deficiencies of P, Mn, and Cu, as well as an excess of Na.



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1. Introduction

The pecan tree (*Carya illinoensis* [Wangenh.] K. Koch) is a crop of great global importance due to the nutritional and economic value of its nut [1,2]. It is grown in 54 countries, with China, the United States, Turkey, Iran, Chile, and Mexico as the main producers [3]. In Mexico, 165,660 hectares were planted in 2024, with a production of 168,733 tons [4].

Pomological parameters, mainly yield and quality, are conditioned by several factors, among which the nutritional status of the trees stands out [5]; this is generally determined through foliar analysis [6,7]. On the other hand, direct kernel analysis has been proposed because it allows us to know the quality of the fruit destined for human consumption [8] and to detect possible nutritional imbalances that are not always reflected in foliar tissue [9].

A problem when analyzing the kernel is that its composition is rich in lipids, which can represent 65 to 75% of its dry weight, making extraction difficult or altering compound quantification [10]. For this reason, some studies perform defatting on kernel samples using solvents [11,12]. As a result, homogeneous samples are obtained, but by reducing the sample mass, results may be altered, since the concentration of some minerals may increase [13] while others may be lost due to mechanical carryover or because they are associated with the lipid fraction of the kernel [14,15].

It is important to consider this bias because most studies report concentrations on a non-defatted kernel basis [16,17]. Others have worked with the defatted basis, especially in studies of bioactive compounds [11,18] and nutritional content [12]. The lack of standardization can hinder comparison among studies. For this reason, correction factors are proposed to transform concentrations on a defatted basis to their non-defatted equivalent. These factors vary according to the element, defatting methodology, and seed type [12,14]. For example, in soybean and flaxseed, defatting has been documented to cause significant losses of P, Mn, Zn, Na, and Mg [14], while in sunflower, losses of Fe and Mg have been reported [15]. For pecan, no studies have reported the effect of defatting on macro- and micronutrient concentrations, nor have specific correction factors been developed for this species.

Another problem is how to interpret kernel nutrient concentrations for use in further research. Comparing with values proposed in the literature is insufficient because it does not consider edaphoclimatic variability and crop management [19]. An alternative is Integrated Differential Diagnosis (IDD), developed by Uvalle-Bueno et al. [20] and applied to crops such as apple [21,22], blueberry [23], pomegranate [24], and pecan [25]. IDD is based on universal biochemical principles (enzyme kinetics, cellular energy charge, and the Q_{10} thermal coefficient) and differs from other systems such as DRIS (Diagnosis and Recommendation Integrated System) and CND (Compositional Nutrient Diagnosis) mainly due to its physiological foundation and its ability to distinguish whether a problem originates from a nutritional or physiological imbalance [20,24].

The objectives of this study were: to determine the effect of defatting on the concentrations of N, P, K, Ca, Mg, Na, Fe, Mn, Zn, and Cu in pecan kernels of the Western Schley variety; to generate correction factors for each element to convert concentrations from a defatted basis to a non-defatted basis; and finally, to generate nutritional sufficiency ranges using the IDD method, both on a defatted basis and on a corrected non-defatted basis, and

to validate these ranges in a different orchard with similar soil and climate conditions but differing management practices.

2. Materials and Methods

2.1. Study Area

The study was carried out in the pecan orchard known as “El Edén,” located in the municipality of Aldama, Chihuahua, Mexico, at geographic coordinates 28.838732° N and 105.893811° W, at an altitude of 1268 m. The region’s climate is classified as semi-arid and warm. During the sampling period (2023–2025), the nearest weather station (“La Mesa”) recorded mean annual temperatures of 19.1, 20.0, and 20.3 °C, and total precipitation of 43.93, 116.15, and 262.51 mm for the years 2023, 2024, and 2025, respectively [26].

2.2. Soil, Water, and Foliar Analysis

Soil characterization was performed based on a sampling conducted during the 2024 agricultural cycle, in the month of September. Soil characterization was conducted to provide a baseline description of the edaphic conditions of the study orchard. Five composite samples were collected at a depth of 0 to 40 cm and air-dried at room temperature. Physicochemical analyses were carried out at the Soil Laboratory of the Faculty of Agrotechnological Sciences of the Autonomous University of Chihuahua. Soil texture was determined using the Bouyoucos hydrometer method [27]. The pH was measured in a 0.01 M CaCl₂ solution (J.T. Baker®, Inc., Radnor, PA, USA), electrical conductivity (EC) was determined from the saturated paste extract, organic matter was quantified using the Walkley and Black method [28], and calcium carbonate content was measured using the open-end manometer technique [29].

Nitrate-N content was determined by the brucine colorimetric method, available phosphorus by the Olsen technique [28], and the major elements K, Ca, Mg, and Na were extracted with 1.0 N ammonium acetate at pH 7.0 (J.T. Baker®, Inc., Radnor, PA, USA) [30]. Micronutrients, including Cu, Fe, Mn, and Zn, were extracted with DTPA (J.T. Baker®, Inc., Radnor, PA, USA) [31]. Finally, the concentration of these elements was determined using an Analyst 100® atomic absorption spectrophotometer (PerkinElmer®, Waltham, MA, USA).

Irrigation water was also analyzed for pH and EC using a multiparameter meter (Hanna Instruments® model HI991301 Woonsocket, RI, USA). The sodium adsorption ratio (SAR) was calculated from the concentrations of Na, Ca, and Mg, which were determined using an Analyst 100® atomic absorption spectrophotometer (PerkinElmer®, Waltham, MA, USA). Based on EC and SAR values, the water was classified according to the U.S. Salinity Laboratory diagram [32,33].

To determine the nutritional status of the trees, foliar sampling was conducted during September of the 2024 agricultural cycle. Leaflets were selected from the middle part of the canopy and from the middle section of the compound leaves, collecting approximately 40 pairs of healthy leaflets per sample. The samples underwent a triple washing process with tap water, 4N HCl, and deionized water, and were subsequently dried in a Heratherm® VCA 230 oven (Thermo Scientific®, Waltham, MA, USA) at a temperature below 60 °C for 72 h. Once dried, they were homogenized using a Wiley® mill (Thomas Scientific, Swedesboro, NJ, USA) equipped with a 1 mm mesh screen.

For chemical analysis, the N concentration was determined by the Kjeldahl method (Novatech®, Houston, TX, USA; Micro Kjeldahl apparatus Labconco®, Kansas, MO, USA) and P by the ammonium metavanadate method. Macronutrients (Ca, K, Mg, and Na) and micronutrients (Fe, Mn, Zn, and Cu) were extracted by triacid digestion (HNO₃:HClO₄:H₂SO₄, 10:10:25 (v:v:v); J.T. Baker®, Inc., Radnor, PA, USA) and quantified by

atomic absorption spectrophotometry using an Analyst 100[®] spectrometer (PerkinElmer[®], Waltham, MA, USA) [34].

2.3. Sample Collection

Additionally, to evaluate the nutritional content of the fruit produced under these conditions, pecan nut samples of the Western Schley variety were collected during the 2023, 2024, and 2025 agricultural cycles. In each year, the harvest was carried out in November; samples were collected during commercial harvest, at full maturity, determined by the natural dehiscence of the husk, obtaining 74 samples, each composed of 30 nuts. The randomly selected trees were all mature, 44-year-old trees, planted at a density of 69 trees ha⁻¹. The average yield reported during the study period was 2.50 t ha⁻¹, with an average of 157 nuts per kilogram.

2.4. Kernel Defatting

For the defatting process, the kernel was manually separated from the shell and ground with an blender (Oster[®] model BLSTPEG-NPB, Mexico City, Mexico) until a fine, homogeneous powder was obtained. Defatting was carried out following the methodology of Villarreal-Lozoya et al. [11] with slight modifications. The ground sample was mixed and homogenized with hexane (J.T. Baker[®], Inc., Radnor, PA, USA) in a 1:20 (*w/v*) ratio. The mixture was vacuum-filtered (Welch Vacuum[®] model 1400, Skokie, IL, USA) at 35 °C using a Büchner funnel (KPM Berlin[®], Berlin, Germany) and low-speed filter paper (Whatman[®], Buckinghamshire, UK). The retained solid was subjected to two additional washes with hexane following the same procedure. Finally, the defatted sample was dried in an oven at 35 °C for 2 h and stored in plastic bags at 4 °C until nutrient analysis.

2.5. Nutrient Analysis

For the nutrient analysis of the defatted pecan kernel basis, N concentration was obtained using the Kjeldahl method (Novatech[®], Houston, TX, USA; Micro Kjeldahl apparatus Labconco[®], Kansas, MO, USA), and P was determined using the ammonium metavanadate method (NH₄VO₃; J.T. Baker[®], Radnor, PA, USA). The determination of the concentration of elements such as Ca, K, Mg, Na, Fe, Mn, Zn, and Cu was performed using triacid digestion (HNO₃:HClO₄:H₂SO₄, 10:10:25 (*v:v:v*); J.T. Baker[®], Radnor, PA, USA), applying 25 mL of the acid mixture on an electric hot plate (RCA[®] model RC2000A, Wilmington, DE, USA) under a fume hood. Element quantification was carried out by atomic absorption spectrophotometry using an Analyst 100[®] spectrometer (PerkinElmer[®], Waltham, MA, USA). It should be noted that the macro- and micronutrient profile analyzed corresponds to the routine foliar analyses that the laboratory offers to producers for the preparation of their fertilization plans; however, in the present study, this same profile was also applied to the kernel.

2.6. Statistical Analysis and Correction Factor

To evaluate the effect of defatting on the concentration of each element, Student's *t*-test for paired samples was used. Sixteen nuts of the same variety and origin were taken; after manually removing the shell, the kernel was separated into two portions: one was analyzed without defatting and the other was defatted according to the previously described protocol. Concentrations of N, P, K, Ca, Mg, Na, Fe, Mn, Zn, and Cu were measured under both conditions, and the data were statistically analyzed using this test with the SAS statistical software, version 9.4 TS Level 1M3 X_64_8HOME Platform (SAS Institute Inc., Cary, NC, USA). Based on the means obtained, the relative correction factor was estimated:

$$Fc = \frac{\bar{x} \text{ Non defatted}}{\bar{x} \text{ Defatted}}$$

A correction factor < 1 indicates that the element becomes concentrated in the defatted fraction. A factor > 1 suggests relative loss.

To verify whether these factors were applicable to the samples from the three years, the concentrations on the defatted basis of the 2023–2025 samples were compared with those of the kernels used for the paired study. No significant differences were found (independent samples *t*-test, $p > 0.05$), indicating that the elemental concentrations of the samples were similar and that the factors could be used. Thus, the mean concentration of each element in the defatted samples from the three years was multiplied by the corresponding correction factor for each element, obtaining the estimated values for non-defatted kernels.

2.7. Integrated Differential Diagnosis

To generate nutritional standards for both the defatted pecan kernel basis and the estimated non-defatted kernel basis, the IDD methodology proposed by Uvalle-Bueno et al. [20] was used. This approach allows us to distinguish whether a nutrient deficiency is related to the availability of elements in the soil or to physiological alterations caused by climatic conditions or plant metabolic processes [21–23,25]. As illustrated in the IDD flowchart (Figure 1) this methodology uses critical values, which are based on universal biochemical principles, such as enzyme kinetics, cellular energy charge, and the Q_{10} thermal coefficient [20,24].

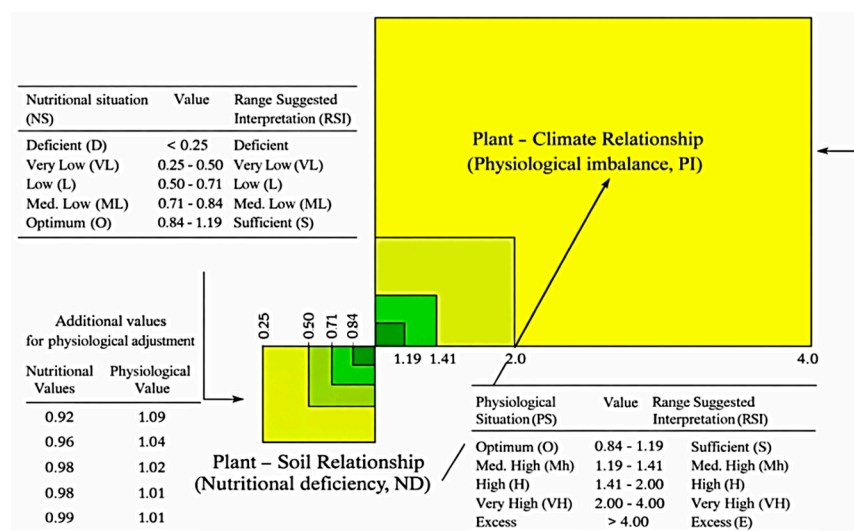


Figure 1. Flowchart for identifying nutritional imbalances (NI) and/or physiological imbalances (PI) and determining the Suggested Interpretation Range (SIR) between observed and ideal conditions. The arrow indicates the transition from the plant–soil relationship (ND) to the plant–climate relationship (PI). The color gradient represents the degree of imbalance: dark green = optimal balance, light green = slight imbalance, and yellow = increasing nutritional or physiological imbalance [23].

To construct the standard, the mean concentration of each nutrient from the 222 analyzed samples was used, without filtering by yield or visual symptoms, assuming that this population represents the typical variability range of the orchard. From this, the intervals for the nine IDD categories were generated by multiplying the mean concentration by each critical value of the scale (0.25, 0.5, 0.71, 0.84, 1.19, 1.41, 2, 4, and 16), where the product obtained for a given critical value corresponds to the upper limit of the associated category. This same procedure was applied to all macro- and micronutrients, using their respective means on a defatted basis and on an estimated non-defatted kernel basis.

2.8. Validation of Standards

For the validation of the standards, pecan nut samples of the Western Schley variety were collected from randomly selected trees during the 2025 growing season from a neighboring orchard, located in the same municipality of Aldama, Chihuahua. It should be mentioned that this orchard has an area of 300 hectares, from which the samples were obtained. This orchard shares the same edaphic and climatic conditions as the “El Edén” orchard, but has different cultural management practices, such as fertilization programs, irrigation, and phytosanitary control.

Soil and foliar analyses were performed according to the procedures described in Section 2.2. No additional water analysis was performed in the neighboring orchard, assuming that conditions are the same because they share the same water supply source.

The first was an external validation with 21 non-defatted kernel samples from the neighboring orchard, compared against the nutritional standard ranges for the estimated non-defatted kernel basis. The second was an additional external validation with 32 defatted samples from the same neighboring orchard, compared against the nutritional standard ranges for the defatted basis. The third was an internal validation with 20 defatted samples from the same “El Edén” orchard, but independent from those used to generate the nutritional standard, also compared against to evaluate internal consistency. Sample size was determined exclusively by the number of kernel samples available in each independent validation dataset. Therefore, the sample size differed among the validation datasets.

3. Results

3.1. Correction Factors Obtained

When comparing the paired means, defatted basis versus non-defatted basis of pecan kernels, significant differences ($p < 0.05$) were observed in practically all analyzed elements. The only exception was Cu, where no significant difference was detected ($p > 0.05$). The correction factors obtained were as follows: N = 0.64, P = 0.62, K = 0.35, Mg = 0.53, Fe = 0.80, Mn = 0.47, Zn = 0.53, Ca = 1.68, Na = 1.55. For Cu, a CF of 1.00 was assumed.

3.2. Nutritional Standards

Tables 1 and 2 present the nutritional standard calculated directly from the concentrations measured in the defatted samples (original basis). Tables 3 and 4 show the values corrected to non-defatted kernels using factors applied only to N, P, K, Mg, Fe, Mn, and Zn. No correction was applied to Ca and Na (they are reported only in Table 1). For Cu, the same concentration is assumed under both conditions.

Table 1. Nutritional standard for the defatted pecan kernel basis for macronutrients (%).

	Range IDD	Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
Nutrient	Mean	0.25	0.5	0.71	0.84	1.19	1.41	2	4	16
N	3.42	<0.86	0.87–1.71	1.72–2.43	2.43–2.87	2.88–4.07	4.08–4.82	4.83–6.84	6.85–13.68	>13.69
P	0.58	<0.15	0.16–0.29	0.30–0.41	0.42–0.49	0.50–0.69	0.70–0.82	0.83–1.16	1.17–2.32	>2.33
K	0.86	<0.21	0.22–0.43	0.44–0.61	0.62–0.72	0.73–1.02	1.03–1.21	1.22–1.72	1.73–3.43	>3.43
Ca	0.23	<0.06	0.07–0.12	0.13–0.16	0.17–0.19	0.20–0.27	0.28–0.32	0.33–0.46	0.47–0.92	>0.93
Mg	0.23	<0.06	0.07–0.12	0.13–0.16	0.17–0.19	0.20–0.27	0.28–0.32	0.33–0.46	0.47–0.92	>0.93
Na	0.0048	<0.0012	0.0013–0.0024	0.0025–0.0034	0.0035–0.0040	0.0041–0.0057	0.0058–0.0068	0.0069–0.0096	0.0097–0.0192	>0.0193

Table 2. Nutritional standard for the defatted pecan kernel basis for micronutrients (mg kg^{−1}).

Range IDD		Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
Nutrient	Mean	0.25	0.5	0.71	0.84	1.19	1.41	2	4	16
Fe	80.9	<20.2	20.3–40.5	40.6–57.4	57.5–68.0	68.1–96.3	96.4–114.1	114.1–161.8	161.9–323.6	>323.7
Mn	148.7	<37.2	37.3–74.4	75.5–105.6	105.7–124.9	125.0–177.0	177.1–209.7	209.8–297.4	297.5–594.8	>594.9
Zn	47.6	<11.9	12.0–23.8	23.9–33.8	33.9–40.0	40.1–56.6	56.7–67.1	67.2–95.2	95.3–190.4	>190.5
Cu	11.4	<2.98	2.99–5.97	5.98–8.47	8.48–10.02	10.03–14.19	14.20–16.81	16.82–23.85	23.86–45.60	>45.61

Table 3. Nutritional standard for the estimated non-defatted pecan kernel basis for macronutrients (%).

Range IDD		Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
Nutrient	Mean	0.25	0.5	0.71	0.84	1.19	1.41	2	4	16
N	2.19	<0.55	0.56–1.10	1.11–1.55	1.56–1.84	1.85–2.60	2.61–3.09	3.10–4.39	4.40–8.76	>8.76
P	0.36	<0.09	0.10–0.18	0.19–0.25	0.26–0.30	0.31–0.42	0.43–0.50	0.51–0.71	0.72–1.42	>1.43
K	0.3	<0.08	0.09–0.15	0.16–0.22	0.23–0.25	0.26–0.36	0.37–0.43	0.44–0.61	0.62–1.21	>1.22
Mg	0.12	<0.03	0.04–0.06	0.07–0.08	0.09–0.10	0.11–0.14	0.15–0.17	0.18–0.24	0.25–0.48	>0.48

Note: Ca and Na are not included in this table because defatting caused actual losses; their values are found in Table 1.

Table 4. Nutritional standard for the estimated non-defatted pecan kernel basis for micronutrients (mg kg^{−1}).

Range IDD		Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
Nutrient	Mean	0.25	0.5	0.71	0.84	1.19	1.41	2	4	16
Fe	64.32	<16.07	16.08–32.16	32.17–45.66	45.67–54.03	54.04–76.54	76.55–90.68	90.68–128.63	128.64–257.26	>257.26
Mn	69.89	<17.47	17.48–34.94	34.95–49.62	49.63–58.71	58.72–83.17	83.18–98.54	98.55–139.78	139.78–279.56	>279.56
Zn	25.04	<6.26	6.27–12.52	12.53–17.78	17.79–21.03	21.04–29.79	29.80–35.30	35.31–50.08	50.09–100.15	>100.16
Cu *	11.4	<2.98	2.99–5.97	5.98–8.47	8.48–10.02	10.03–14.19	14.20–16.81	16.82–23.85	23.86–45.60	>45.61

Note: * Copper was not corrected (non-significant difference); its original value from the defatted basis is presented as reference.

3.3. Characteristics of the Validation Sites

To facilitate interpretation of the validation results, Table 5 compares soil, foliar, and water conditions between the “El Edén” orchard, where the standards were generated, and the neighboring orchard used for external validation.

Table 5. Integrated comparison of soil-foliar-water conditions between the standard generation orchard (“El Edén”) and the validation orchard (neighboring).

Level	Parameter	“El Edén” Orchard	Neighboring Orchard	Observed Congruence
Soil	Texture	Clay loam	Clay loam	Similar
	pH	7.56	7.78	Higher in neighbor
	EC (dS m ^{−1})	0.88	2.02	Higher in neighbor
	CaCO ₃ (%)	4.37	2.33	Lower in neighbor
	MO (%)	1.74	0.51	Lower in neighbor
	N (g kg ^{−1})	0.0658	0.0460	Lower in neighbor
	P (g kg ^{−1})	0.0319	0.00764	Lower in neighbor
	K (g kg ^{−1})	0.333	0.443	Higher in neighbor
	Ca (g kg ^{−1})	2.87	3.45	Higher in neighbor
	Mg (g kg ^{−1})	0.492	0.406	Lower in neighbor
	Na (g kg ^{−1})	0.508	0.815	Higher in neighbor
	Cu (mg kg ^{−1})	1.84	0.56	Lower in neighbor
	Fe (mg kg ^{−1})	2.84	1.11	Lower in neighbor
	Mn (mg kg ^{−1})	11.71	5.03	Lower in neighbor
	Zn (mg kg ^{−1})	8.44	1.25	Lower in neighbor

Table 5. Cont.

Level	Parameter	“El Edén” Orchard	Neighboring Orchard	Observed Congruence
Foliar	N (g kg ⁻¹)	25.1	27.9	Higher in neighbor
	P (g kg ⁻¹)	1.8	2.5	Higher in neighbor
	K (g kg ⁻¹)	9.7	11.6	Higher in neighbor
	Ca (g kg ⁻¹)	26.2	16.4	Lower in neighbor
	Mg (g kg ⁻¹)	5.0	10.5	Higher in neighbor
	Na (g kg ⁻¹)	0.13	0.30	Higher in neighbor
	Cu (mg kg ⁻¹)	6.04	7.62	Higher in neighbor
	Fe (mg kg ⁻¹)	135.82	142.88	Higher in neighbor
	Mn (mg kg ⁻¹)	899.82	527.42	Lower in neighbor
	Zn (mg kg ⁻¹)	48.66	35.92	Lower in neighbor
Water	pH	7.94	--	The same water source
	CE (dS m ⁻¹)	0.335	--	
	SAR	4.71	--	
	Classification	C2-S1	--	

3.4. Validation of Nutritional Standards

3.4.1. External Validation with Non-Defatted Samples

Twenty-one non-defatted kernel samples from a neighboring orchard were analyzed. These values were directly compared with the standard corrected to non-defatted kernels (Tables 3 and 4). The results are shown in Table 6.

Table 6. Classification of 21 non-defatted kernel samples from the neighboring orchard according to the nutritional standard for the estimated non-defatted pecan kernel basis (Tables 3 and 4).

Nutrient	Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
N	0	0	0	0	16	5	0	0	0
P	21	0	0	0	0	0	0	0	0
K	0	0	4	6	10	1	0	0	0
Mg	0	0	0	0	0	0	16	5	0
Fe	0	0	0	0	14	6	1	0	0
Mn	0	4	6	11	0	0	0	0	0
Zn	0	0	0	1	13	4	3	0	0
Cu	0	0	5	16	0	0	0	0	0

All samples were deficient in P, Mn, and Cu. This coincides with soil analyses of the neighboring orchard (Table 5), which reported low concentrations of P (18.33 kg ha⁻¹), Mn (5.03 mg kg⁻¹), and Cu (0.56 mg kg⁻¹). In contrast, N, Fe, and Zn showed a majority of samples in the sufficient range (76%, 67%, and 62%, respectively). For Mg, most samples were classified as high and very high in the neighboring orchard, reflecting soil conditions (EC = 2.02 dS m⁻¹, Na = 815 mg kg⁻¹), which differ from those at sites reported in the international literature.

3.4.2. External Validation with Defatted Samples

Thirty-two defatted pecan kernel samples from the same neighboring orchard were analyzed and compared with the standard on a defatted basis (Tables 1 and 2). The results are shown in Table 7.

Table 7. Classification of 32 defatted pecan kernel samples from the neighboring orchard according to the nutritional standard for the defatted basis (Tables 1 and 2).

Nutrient	Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
N	0	0	0	2	23	6	1	0	0
P	0	0	1	5	25	1	0	0	0
K	0	0	2	20	10	0	0	0	0
Ca	0	2	7	10	12	0	1	0	0
Mg	0	0	0	5	12	13	2	0	0
Na	0	0	0	0	0	9	10	13	0
Fe	0	0	0	4	8	1	19	0	0
Mn	0	0	10	7	12	3	0	0	0
Zn	0	0	0	0	1	10	21	0	0
Cu	1	0	11	10	9	1	0	0	0

Na concentrations were entirely classified above the sufficient range (41% in “very high”), which is consistent with the high electrical conductivity of the neighboring orchard soil (2.02 dS m^{-1}) and its elevated Na concentration ($815.22 \text{ mg kg}^{-1}$) (Table 5). Fe and Zn concentrations showed a tendency toward high values, with 59% and 66% in “high”, respectively. A difference was observed in P classification between Table 4 (all deficient) and Table 5 (78% sufficient).

3.4.3. Internal Validation

To evaluate whether the nutritional standard on a defatted basis has internal consistency, 20 defatted samples from the same “El Edén” orchard, different from those used to generate the standard, were compared against (Tables 1 and 2). The results are shown in Table 8.

Table 8. Classification of 20 defatted pecan kernel samples from the “El Edén” orchard against the nutritional standard for the defatted basis (Tables 1 and 2).

Nutrient	Deficient (D)	Very Low (vL)	Low (B)	Medium Low (ML)	Sufficient (S)	Medium High (MH)	High (H)	Very High (vH)	Excess (E)
N	0	0	0	2	16	2	0	0	0
P	0	0	0	5	11	4	0	0	0
K	0	0	0	3	14	3	0	0	0
Ca	0	1	1	4	9	5	0	0	0
Mg	0	0	0	3	11	4	1	0	0
Na	0	0	0	1	18	0	0	1	0
Fe	0	0	0	1	13	5	1	0	0
Mn	0	0	0	4	13	3	0	0	0
Zn	0	2	0	1	13	4	0	0	0
Cu	0	0	2	5	7	5	1	0	0

Between 55% and 90% of the samples per nutrient fell into the “sufficient” category, with the highest values for N (80%), K (70%), Na (90%), and Mn (65%). This behavior is consistent with soil analyses of the “El Edén” orchard (Table 5), which showed adequate concentrations of N ($157.92 \text{ kg ha}^{-1}$), K ($333.25 \text{ mg kg}^{-1}$), and Mn (11.71 mg kg^{-1}), as well as a moderate Na level ($507.50 \text{ mg kg}^{-1}$) that did not generate toxicity in the kernel. The presence of some samples in categories from moderately low to moderately high reflects the natural variability of the orchard and is expected for a nutritional standard constructed from the mean of a high-yielding population. This confirms the internal validity of the standard.

4. Discussion

4.1. Effect of Defatting on Nutrient Concentration

The pecan kernel contains approximately 65–75% lipids, while proteins, fiber, carbohydrates, and minerals make up 25–35% [11,35]. It has been demonstrated that oil extraction, using mechanical or chemical methods, often leads to a higher concentration of nutrients compared to non-defatted samples [12,14]. This may be because once the oil is extracted, the total sample weight decreases while nutrients remain in the defatted fraction, increasing their concentration per gram of sample [14]. In this study, the same behavior was observed for most of the analyzed elements, including N, P, K, Mg, Fe, Mn, and Zn, confirming that lipid extraction with hexane concentrated these nutrients in the defatted fraction. However, defatting does not always lead to an increase in mineral concentration, as some elements may be lost due to mechanical carryover during lipid extraction. This has been documented in soybean seeds (losses of P, Mn, and Zn) [14], flaxseed (Na and Mg) [13,14], and sunflower seeds (Fe and Mg) [15].

In the present study, this behavior was particularly evident for Ca and Na, whose concentrations decreased after defatting, in contrast to most other elements, which became concentrated due to the removal of the lipid fraction. For Cu, no significant differences were found; this can be explained by a compensation between the increase in concentration due to lipid removal and the loss of Cu associated with the lipid fraction or by mechanical carryover, similar to that reported for Fe(III) and Li in flaxseed [13].

The decrease in Ca and Na in pecan nut kernel samples defatted with hexane could be related to the removal of extractable components associated with the lipid fraction or to the carryover of fine mineral particles during filtration. This behavior coincides with that reported by Adeosun et al. [36], who found that hexane favored greater extraction of Ca and Na from *Hunteria umbellata* seeds compared to ethanol, suggesting that solvent properties may influence the recovery of certain minerals during extraction. In contrast, Welna et al. [37] observed that Ca remained in the defatted residues of Brazil nuts (*Bertholletia excelsa*) after extractions with petroleum ether and chloroform:methanol. These differences suggest that the mineral response to defatting depends on the plant species, the solvent used, and the chemical form of the elements.

The hexane-based defatting protocol used in this study offers advantages in terms of operational simplicity, reproducibility, and low cost [10,11]; however, its main limitation is the possible mechanical carryover of fine mineral particles during vacuum filtration. Therefore, these findings highlight the importance of clearly reporting the defatting conditions, including the type of solvent, when presenting mineral composition data in lipid-rich samples, in order to ensure comparability among studies.

4.2. Correction Factors

The correction factors obtained will allow the transformation of concentrations measured on a defatted basis to their non-defatted equivalent. The usefulness of these factors was confirmed by comparing the concentrations of samples from three consecutive years (2023–2025) with those used in the paired study, finding no significant differences ($p > 0.05$).

Comparison of the nutritional standard obtained from the corrected data (Tables 3 and 4) with values reported in the literature showed greater agreement than when using the standard derived directly from the defatted basis (Tables 1 and 2), since the latter values were considerably higher than those documented by various authors [16,17,38]. For example, the K sufficiency range on a defatted basis (0.73–1.02%) is much higher than that typically reported in non-defatted kernels [8,17], whereas the corrected range (0.26–0.36%) agrees with those reports. This reinforces the need to use correction factors when comparing stud-

ies that use different reporting bases (defatted vs. non-defatted), and it is recommended that future studies explicitly specify the defatting status of samples.

4.3. Comparison with the Literature and Validation of Nutritional Standards

Comparison of the nutritional standard obtained from the corrected data (Tables 3 and 4) with values reported in the literature showed greater similarity than when using the standard derived directly from the defatted basis (Tables 1 and 2), since the latter values were higher than those reported by several authors.

For nitrogen, the corrected sufficiency range (1.85–2.60%) coincides with that found by Çelik [17] in Turkey, who reported an N percentage of 1.85%. For phosphorus, the sufficiency range (0.31–0.42%) showed greater similarity with concentrations reported for different pecan varieties grown in Mexico, Uruguay, the United States, and Australia. The values reported for the Western variety in Australia (0.325%) coincide with our ranges, this being the same variety used in the present study [8,16,19,39].

Potassium showed behavior similar to that previously reported, reinforcing the reliability of the ranges obtained in this study. Flores-Córdova et al. [8] found concentrations of 0.326% in the Western variety and 0.367% in the Wichita variety, both grown in Mexico. Likewise, similarity was observed with values reported in Turkey, China, and Poland [17,27,40].

Regarding Mg, its obtained correction factor (0.53) allowed the nutritional standard on a non-defatted basis (0.11–0.14%) to agree with values reported for the Western variety in Australia [39], Mexico [8], Uruguay [19], and China [41]. However, under high salinity and sodicity conditions (neighboring orchard), the Mg concentration in kernels was higher (classified as high/very high), which is consistent with the higher Mg concentration in foliar analysis (1.05%) and suggests that the correction factor is consistent even under contrasting edaphic conditions.

Regarding calcium, the sufficiency range obtained on a defatted basis (0.20–0.27%) showed agreement only with that reported by Moodley et al. [12] in South Africa (0.208% Ca), who also performed mineral determination using defatted samples. The lack of agreement with most studies that did not employ defatting suggests that calcium in pecan nut kernels may be associated with components of the lipid fraction that are removed during extraction, or that its recovery may be affected by the mechanical carryover of fine particles during filtration. These results reinforce the importance of explicitly reporting the defatting status of samples when comparing calcium concentrations across studies.

Regarding sodium, based on the sufficiency range of the nutritional standard on the defatted basis (0.0041–0.0057%), great variability was observed compared to values reported by different authors. Literature values ranged from deficient to high or very high within the generated standard [8,40]. The only agreement within the sufficiency range was with that reported by Wakeling et al. [39] in Australia for the Western variety, with a Na value of 0.0047%.

Regarding manganese, the sufficiency range (58.72–83.17 mg kg⁻¹) was consistent with that reported by most of the consulted authors for different varieties and regions of the world [19,39,41]. The agreement with findings in China and Australia for the Western variety is notable, where concentrations of 65.6 and 83.0 mg kg⁻¹ are reported, respectively.

On the other hand, the iron sufficiency range (54.04–76.54 mg kg⁻¹) agrees with a large proportion of varieties grown in China, notably coinciding with the Western variety, with a value of 65.6 mg kg⁻¹ [41].

In the case of zinc, most concentrations found in the literature are classified in the moderately high [8], high [19,38,41] to very high [39] ranges. However, the Zn concentration of 27 mg kg⁻¹ reported by Çelik [17] in Turkey coincides with our sufficiency range. The discrepancy between our ranges and most international reports could reflect lower zinc

availability in the soils of the Aldama region, resulting in a lower concentration in the kernel, or differences in the absorption efficiency of the Western Schley variety under local edaphoclimatic conditions.

Finally, the only element that showed no significant difference in the paired study between the defatted and non-defatted samples was copper. Its concentration in our ranges is consistent with that reported in other studies, coinciding with our sufficiency range ($10.03\text{--}14.19\text{ mg kg}^{-1}$) [16,19,40].

It is worth noting that, for every element analyzed, some degree of discrepancy was found among the different literature sources consulted. This variability was expected, since the mineral composition of pecan kernels is influenced by several factors, such as the use of different cultivars [8,19,39], the specific edaphoclimatic conditions of each region, including pH, salinity, and soil texture [26,32], and orchard agronomic management, including fertilization, irrigation, and pest/disease control [5,18]. All of these factors directly influence the absorption and accumulation of minerals in the kernel.

Some reports on the mineral composition of pecan kernels, such as that of Curiel-Maciél et al. [42], present concentrations well above those normally documented in the literature, which may limit their usefulness as a nutritional reference for kernels. This reinforces the need to generate regional nutritional standards using methodologies such as IDD.

Although the IDD method has previously been applied to various crops for the generation of nutritional standards, most of these studies have not incorporated any type of external or internal validation [22–25]. In this context, the present study provides an additional approach by evaluating the consistency of the generated standards through their application under independent field conditions.

External validation in a neighboring orchard with different management but similar edaphoclimatic conditions demonstrated the ability of the generated standards to detect nutritional imbalances consistent with soil analyses. The 21 non-defatted samples from the neighboring orchard were all classified as deficient in P, Mn, and Cu (Table 6), which coincides with the low levels of these elements present in the soil of that orchard (P: 18.33 kg ha^{-1} , Mn: 5.03 mg kg^{-1} , Cu: 0.56 mg kg^{-1}). Likewise, external validation with 32 defatted samples from the same orchard showed that 100% of the samples classified above the sufficient range for Na (41% in “very high”), consistent with the high electrical conductivity (2.02 dS m^{-1}) and high Na content in the soil (815.22 mg kg^{-1}).

In the internal validation with 20 samples from the same “El Edén” orchard, it was found that between 55% and 90% of samples per nutrient were classified in the “sufficient” category, with the highest values for N (80%), K (70%), Na (90%), and Mn (65%). This behavior is consistent with the soil analysis of the “El Edén” orchard, which showed adequate concentrations of N (157.92 kg ha^{-1}), K (333.25 mg kg^{-1}), and Mn (11.71 mg kg^{-1}). The presence of some samples in categories from moderately low to moderately high reflects the natural variability of the orchard and is expected for a nutritional standard constructed from the mean of a high-yielding population.

Climatic conditions during the sampling period (2023–2025) showed a marked variation in precipitation (43.9 to 262.5 mm), while temperature remained stable ($19\text{--}20\text{ }^{\circ}\text{C}$) [26]. These environmental differences could have influenced soil nutrient availability and their translocation to the seed. Precipitation, in particular, is a factor that affects the mobility of elements such as K and Mn [32], whose availability typically increases with soil moisture. In contrast, Na tends to concentrate under water deficit and low precipitation conditions, whereas abundant rainfall may favor its leaching from the soil profile [32,33]. Indeed, in the external validation of the nutritional standard, 100% of the samples from the neighboring orchard were classified above the sufficient range for Na, which was consistent with the

high electrical conductivity (2.02 dS m^{-1}) and the elevated soil Na content ($815.22 \text{ mg kg}^{-1}$) at that site (Table 5).

Overall, the three validation exercises demonstrate that the nutritional standards generated by IDD are sensitive to differences in soil nutrient availability and are internally consistent, supporting their use as a nutritional diagnostic tool in pecan orchards in the Aldama region, Chihuahua, Mexico.

5. Conclusions

Based on the results obtained in this study, it was found that defatting of pecan kernels with hexane affects the concentration of the analyzed elements. Notably, there was a significant increase in the concentration of N, P, K, Mg, Fe, Mn, and Zn due to the reduction in kernel mass from the lipid fraction. In contrast, Na and Ca showed a significant loss in concentration, which may be due to actual loss by mechanical carryover during the defatting process. Finally, Cu concentration was not significantly affected by the methodology employed.

Nutritional sufficiency ranges for pecan kernels were established using the IDD methodology, both for the defatted basis and for the estimated non-defatted basis. The corrected ranges showed high agreement with values reported in the literature for non-defatted kernels, validating the correction procedure. In contrast, the ranges on the defatted basis were notably higher, demonstrating the need to apply correction factors when comparing studies that use different reporting bases.

The three validation exercises (external validation with non-defatted samples, external validation with defatted samples, and internal validation) demonstrated that the generated nutritional standards are consistent. The standards detected nutritional imbalances in the neighboring orchard, which were congruent with the soil analyses of that orchard. Internal validation in the “El Edén” orchard showed that between 55% and 90% of the samples were classified in the “sufficient” category, adequately reflecting the nutritional conditions of the site of origin.

It is recommended that future research on the mineral composition of pecan kernels explicitly state whether samples were defatted or not. When using a defatted basis, the application of the correction factors proposed here will allow a more precise comparison with existing literature. The generated IDD nutritional standards constitute a reliable diagnostic tool for pecan orchards in the Aldama region, Chihuahua, Mexico.

A limitation of this study is that the standards were generated from a single population and validated in only one neighboring orchard with similar conditions. Although the IDD method has been used with this approach to establish regional sufficiency ranges, it is essential to highlight the need to obtain a larger number of samples from different regions of the state, covering different edaphoclimatic conditions. This is essential to generate a robust and representative standard at the state level before making extensive use of the proposed standards. However, it should be noted that the IDD methodology can be extrapolated to other regions, to other quantitative measurements, and even to other crops.

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References

- Ortiz-Quezada, A.G.; Lombardini, L.; Cisneros-Zevallos, L. Antioxidants in pecan nut cultivars [*Carya illinoensis* (Wangenh.) K. Koch]. In *Nuts and Seeds in Health and Disease Prevention*; Preedy, V.R., Watson, R.R., Patel, V.B., Eds.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 881–889.
- Zhang, R.; Peng, F.; Li, Y. Pecan production in China. *Sci. Hortic.* **2015**, *197*, 719–727. [CrossRef]
- FAO. *Food and Agriculture Organization Statistical Database*; FAO: Rome, Italy, 2025. Available online: <https://www.fao.org/faostat/es/#data/QCL> (accessed on 15 February 2026).
- Servicio de Información Agroalimentaria y Pesquera. *Producción Agrícola. Histórico de Siembra y Cosecha*; Servicio de Información Agroalimentaria y Pesquera: Mexico City, Mexico, 2024. Available online: https://nube.agricultura.gob.mx/cierre_agricola (accessed on 20 February 2026).
- Orozco-Meléndez, L.R.; Noperi-Mosqueda, L.C.; Oviedo-Mireles, J.C.; Torres-Beltrán, N.G.; Yáñez-Muñoz, R.M.; Soto-Parra, J.M. Balanced Fertilization with Nitrogen, Molybdenum, and Zinc: Key to Optimizing Pecan Tree Yield and Quality of Western Schley Pecan Tree. *Horticulturae* **2025**, *11*, 741. [CrossRef]
- Smith, M.W.; Rohla, C.T.; Goff, W.D. Pecan Leaf Elemental Sufficiency Ranges and Fertilizer Recommendations. *HortTechnology* **2012**, *22*, 594–599. [CrossRef]
- Smith, C.A.; VanLeeuwen, D.; Heerema, R.J.; Sherman, J.D.; Comeau, M.J.; Walworth, J.L. Zinc Variability in Pecan Orchards: Implications for Leaf Sampling and Nutrient Recommendations. *HortScience* **2022**, *57*, 550–557. [CrossRef]
- Flores-Córdova, M.A.; Sánchez Chávez, E.; Chávez-Mendoza, C.; García-Hernández, J.L.; Preciado-Rangel, P. Bioactive compounds and phytonutrients in edible part and nutshell of pecan (*Carya illinoensis*). *Cogent Food Agric.* **2016**, *2*, 1262936. [CrossRef]
- Binkley, D.; Stape, J.L.; Albaugh, T.J. Foliar nutrient concentrations and stoichiometry should not be assumed to diagnose nutrient limitation. *Ecol. Process.* **2025**, *14*, 27. [CrossRef]
- Toro-Vazquez, J.F.; Charo-Alonso, M.A.; Perez-Briceno, F. Fatty acid composition and its relationship with physicochemical properties of pecan (*Carya illinoensis*) oil. *J. Am. Oil Chem. Soc.* **1999**, *76*, 957–965. [CrossRef]
- Villarreal-Lozoya, J.E.; Lombardini, L.; Cisneros-Zevallos, L. Phytochemical constituents and antioxidant capacity of different pecan [*Carya illinoensis* (Wangenh.) K. Koch] cultivars. *Food Chem.* **2007**, *102*, 1241–1249. [CrossRef]
- Moodley, R.; Kindness, A.; Jonnalagadda, S.B. Elemental composition and chemical characteristics of five edible nuts (almond, Brazil, pecan, macadamia and walnut) consumed in Southern Africa. *J. Environ. Sci. Health Part. B* **2007**, *42*, 585–591. [CrossRef]
- Petraru, A.; Amariei, S.; Senila, L. Flaxseed Oilcake: An Ingredient with High Nutritional Value in the Realization of Innovative Food Products. *Foods* **2025**, *14*, 1087. [CrossRef] [PubMed]
- Kolláthová, R.; Varga, B.; Ivanišová, E.; Bíro, D.; Rolínek, M.; Juráček, M.; Šimko, M.; Gálik, B. Mineral profile analysis of oilseeds and their by-products as feeding sources for animal nutrition. *Slovak. J. Anim. Sci.* **2019**, *52*, 9–15.
- Petraru, A.; Ursachi, F.; Amariei, S. Nutritional characteristics assessment of sunflower seeds, oil and cake. Perspective of using sunflower oilcakes as a functional ingredient. *Plants* **2021**, *10*, 2487. [CrossRef] [PubMed]
- Senter, S.D. Mineral composition of pecan nutmeats. *J. Food Sci.* **1976**, *41*, 963–964. [CrossRef]
- Celik, S.A. Determination of physico-mechanical and chemical properties of pecan [*Carya illinoensis* (Wangenh.) K. Koch] grown in Türkiye. *Erwerbs-Obstbau* **2024**, *66*, 1983–1990. [CrossRef]
- Noperi-Mosqueda, L.C.; Soto-Parra, J.M.; Sánchez, E.; Piña-Ramírez, F.J.; Pérez-Leal, R.; Flores-Córdova, M.A.; Salas-Salazar, N.A. Impact of Organic and Mineral Fertilization in Pecan Nut on Production, Quality and Antioxidant Capacity. *Agric. Sci.* **2019**, *10*, 227–240. [CrossRef]
- Ferrari, V.; Gil, G.; Heinzen, H.; Zoppolo, R.; Ibáñez, F. Influence of cultivar on nutritional composition and nutraceutical potential of pecan growing in Uruguay. *Front. Nutr.* **2022**, *9*, 868054. [CrossRef] [PubMed]

20. Uvalle-Bueno, J.X.S.; Alcalde-Blanco, S.; Kick, H. Fundamentos fisiológicos del diagnóstico diferencial integrado (DDI). In *Memorias del XXVI Congreso Nacional de la Ciencia del Suelo*; Cd. Victoria: Tamaulipas, Mexico, 1995; p. 51.
21. Soto, J.M.; Hernández, A.P.; Uvalle-Bueno, J.X.; Yáñez, R.M.; Montes, F.; Sánchez, E.; Romero, L. Relación del estado nutricional y la intensidad de mancha amarga en frutos de manzano “Golden Delicious” en postcosecha. *Ars. Pharm.* **1999**, *40*, 241–245.
22. Mancera-López, M.M.; Soto-Parra, J.M.; Sánchez-Chávez, E.; Yáñez-Muñoz, R.M.; Montes-Domínguez, F.; Balandrán-Quintana, R.R. Caracterización mineral de manzana ‘Red Delicious’ y ‘Golden Delicious’ de dos países productores. *TECNOCENCIA Chihuahua*. **2007**, *1*, 6–17. [[CrossRef](#)]
23. Yáñez-Muñoz, R.M.; Soto-Parra, J.M.; Pérez-Leal, R.; Piña-Ramírez, F.J.; Acevedo-Barrera, A.A. Estándares nutricionales foliares para arándano (*Vaccinium corymbosum* L.) mediante diagnóstico diferencial integrado (DDI), en Chihuahua. *TECNOCENCIA Chihuahua*. **2018**, *12*, 182–192.
24. Torres-Beltrán, N.G.; Yáñez-Muñoz, R.M.; Soto-Parra, J.M.; Noperi-Mosqueda, L.C. Nutritional standards through Integrated Differential Diagnosis (IDD) in pomegranate (*Punica granatum* L.). *Not. Bot. Horti Agrobot. Cluj-Napoca* **2023**, *51*, 12988. [[CrossRef](#)]
25. Alanís-Fierro, A.K.; Soto-Parra, J.M.; Sánchez-Chávez, E.; Yáñez-Muñoz, R.M.; Piña-Ramírez, F.J. Caracterización del estado nutricional foliar para níquel en nogal pecanero. *Rev. Cient. Biol. Agropecu. Tuxpan* **2014**, *2*, 65–70. [[CrossRef](#)]
26. Comisión Nacional del Agua. Estaciones Climatológicas. Available online: <https://sih.conagua.gob.mx/climas.html> (accessed on 27 June 2026).
27. Gee, G.W.; Bauder, J.W. Particle size density. In *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*; Klute, A., Ed.; SSSA: Madison, WI, USA, 1986.
28. Aguilar Santelises, A.; Etchevers Barra, J.D.; Castellanos Ramos, J.Z. *Chemical Analysis to Evaluate Soil Fertility*; Mexican Society of Soil Science: Chapingo, Mexico, 1987; Volume I, p. 214.
29. Presley, B.J. A simple method for determining calcium carbonate in sediment samples. *J. Sediment. Petrol.* **1975**, *45*, 745–746. [[CrossRef](#)]
30. Lindsay, W.L.; Norvell, W.A. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* **1978**, *42*, 421–428. [[CrossRef](#)]
31. Thomas, G.W. Exchangeable cations. In *Methods of Soil Analysis*, 2nd ed.; Page, A.L., Ed.; Agronomy No. 9, Part 2; American Society of Agronomy Inc.: Madison, WI, USA, 1982.
32. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils*; U.S. Department of Agriculture: Washington, DC, USA, 1954; Volume 60.
33. Ponsadai Lakshmi, S.; Gopi, C.; Adwin Jose, P. Mamdani-type fuzzy inference system for irrigational water quality. *J. Niger. Soc. Phys. Sci.* **2024**, *6*, 1890. [[CrossRef](#)]
34. Orozco-Meléndez, L.R.; Hernández-Rodríguez, O.A.; Cruz-Alvarez, O.; Benavides-Mendoza, A.; Calderón-Jurado, M.; Ojeda-Barrios, D.L. Does the application of growth bioregulators improve the foliar concentration of nutrients, non-structural carbohydrates and yield in pecan? *Ciênc. Agrotec.* **2021**, *45*, e004721. [[CrossRef](#)]
35. Chang, J.; Yang, S.P.; Yao, X.H.; Zhang, X.D.; Wang, K.L.; Ren, H.D.; Wu, J.R.; Zhang, J.; Yang, Y. Evaluation of fruit traits, kernel nutrition, and fatty acid composition of ten pecan varieties for edible oil production. *Forests* **2022**, *13*, 25.
36. Adeosun, Y.M.; Adeosun, O.C.; Oni, I.O. A Comparative Study of N-Hexane and Ethanol Extraction in Abeere *Hunteria umbellata* Seed Oil for Assessing Mineral Profiles. *Asian J. Res. Bios.* **2024**, *6*, 230–236.
37. Welna, M.; Klimpel, M.; Żyrmicki, W. Investigation of major and trace elements and their distributions between lipid and non-lipid fractions in Brazil nuts by inductively coupled plasma atomic optical spectrometry. *Food Chem.* **2008**, *111*, 1012–1015. [[CrossRef](#)]
38. Sparks, D. Concentration and content of 14 elements in fruit of pecan. *HortScience* **1975**, *10*, 517–519. [[CrossRef](#)]
39. Wakeling, L.T.; Mason, R.L.; D’Arcy, B.R.; Caffin, N.A. Composition of pecan cultivars Wichita and Western Schley [*Carya illinoensis* (Wangenh.) K. Koch] grown in Australia. *J. Agric. Food Chem.* **2001**, *49*, 1277–1281. [[CrossRef](#)] [[PubMed](#)]
40. Woźniak, M.; Waśkiewicz, A.; Ratajczak, I. The content of phenolic compounds and mineral elements in edible nuts. *Molecules* **2022**, *27*, 4326. [[CrossRef](#)] [[PubMed](#)]
41. Wu, S.; Yao, X.; Wang, K.; Yang, S.; Ren, H.; Huang, M.; Chang, J. Quality analysis and comprehensive evaluation of fruits from different cultivars of pecan (*Carya illinoensis* (Wangenheim) K. Koch). *Forests* **2022**, *13*, 746. [[CrossRef](#)]
42. Curiel-Macié, N.F.; Arreola-Ávila, J.G.; Esparza-Rivera, J.R.; Luna-Zapién, E.A.; Minjares-Fuentes, J.R.; Sierra-Campos, E.; Meza-Velázquez, J.A. Nutritional quality, fatty acids content and antioxidant capacity of pecan nut fruits from Criolla and Improved walnut varieties. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2021**, *49*, 12021. [[CrossRef](#)]

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