FINAL REPORT

TITLE: STUDY OF THE EXPERIMENTAL EFFECT OF THE PRODUCT EF Polymer (AN ECO-FRIENDLY POLYMER OF JAPANESE ORIGIN MANUFACTURED BY EP Polymer Co., Ltd.) ON LETTUCE CULTIVATION UNDER AGROECOLOGICAL CONDITIONS IN THE AGUASCALIENTES VALLEY

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EXPERIMENTAL FIELD, PABELLÓN

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INTRODUCTION

The national lettuce production volume is approximately 552,940 metric tons. The main producing states are: Guanajuato (27%), Zacatecas (18%), Puebla (14%), and Aguascalientes (12%), which produces approximately 67,000 metric tons of lettuce annually, on an area of approximately 1,850 hectares (SIAP, 2025).

To meet food production demand and satisfy the needs of an ever-growing population, substantial improvements are needed in production processes, as well as the integration of technologies and innovations that make production systems more efficient; as is well known, agricultural activities account for about 70 percent of the planet's freshwater, the availability of which has been declining; therefore, it is necessary to incorporate components that improve efficiency and increase crop productivity.

One alternative could be the use of naturally derived polymers that help counteract the effects of drought and soil degradation, increase the efficiency of water and fertilizer use, reduce costs, and thereby address the effects of climate change and water scarcity.

Based on this, innovative solutions for sustainable production are emerging. One such solution is EF Polymer (2023), a plant-based, 100% biodegradable polymer developed to improve water retention in the soil and increase crop productivity.

EF Polymer acts like a natural sponge: it absorbs available water and gradually releases it to the roots, reducing the need for irrigation and minimizing water stress. It is neither a fertilizer nor a chemical additive, but rather a complementary tool that supports healthy crop growth under difficult conditions.

Therefore, this company is interested in evaluating the effect of EF Polymer on productivity and the efficiency of water and fertilizer use in different crops, including a proposed lettuce crop for the spring 2026 growing season in the northern region of the Aguascalientes Valley.

OBJECTIVE:

To evaluate different doses of EF Polymer in lettuce cultivation to determine its biological effectiveness on yield, water use efficiency, and fertilizer application rates.

METHODOLOGY

Study site. The study was conducted at the Pabellón Experimental Farm, located at 1,907 meters above sea level, where a temperate, semi-arid climate prevails with an average temperature of 16.8°C and an average annual precipitation of 456 mm (García, 1964; Medina *et al*., 1998, 2006). The evaluation included three factors under study: a) irrigation requirements of 75% and 100% of the crop's actual evapotranspiration (ETr), b) fertilizer treatment (80% and 100% of the fertilizer treatment), and c) polymer at doses of 0, 18.08, 36.08, and 52.80 kg/ha; the combination of the three factors under study was carried out using a 3^{K} factorial ^{design}, resulting in 16 treatments (Table a.18) in the Appendix. The soil where the experiment was conducted is loamy in texture (Flores and Alcalá, 2010), with a pH of 8.09, organic matter content of 1.07%, electrical conductivity of 0.55 dS/m, and a bulk density of 1.42 g/cm^3 (Figures a.1 and a.2 in the Appendix). The irrigation water has a pH of 7.01 and an electrical conductivity of 0.72 dS/m, with a mild to moderate degree of salinity (Figure a.3) in the Appendix. In addition, the soil moisture retention curve was determined in the laboratory (Figure a.5) in the Appendix.

Experimental design. A randomized block design with four replicates was used in a split-plot arrangement, where the large plot was the irrigation factor (A), the medium plot was the fertilization factor (B), and the small plot was the polymer dose (C); each experimental unit consisted of six furrows spaced 0.90 m apart and 25.0 m long, and the experimental area comprised the two central furrows.

Agronomic management. The Judalinas RZ variety was used, recommended for the spring-summer growing season, with resistance to tip burn and *Fusarium spp*., and a vegetative cycle of 95 to 100 days.

Greenhouse sowing took place on January 20. Soil preparation was carried out during January and early February. On February 25 and 26, the fertilizer and polymer treatments were applied manually in their respective doses to the center of the furrow at a depth of 15 cm; the fertilizer was then covered manually with a rake, and the furrow was formed using machinery on February 27. On March 3, a tool called a “bed former” was used to install the drip tape, mark the rows, and form the planting beds.

Before the first irrigation, the herbicides Pendimethalin (pre-emergent) at a dose of 1 L/ha and Clethodim (post-emergent) at a dose of 0.5 L/ha were applied to areas with isolated patches of perennial grass. Planting was carried out on
March 10, 2026, manually in moist soil, using a double-row, staggered planting pattern with plants spaced 0.30 m apart and row spacing of 0.30 m on 0.40 m-wide beds, to achieve a planting density of 74,000 plants/ha. The fertilizer treatment was 140N-86P-215K_2O-25Ca-15MgO for 100% of the application and 112N-68.8P-169.6K_2O-20Ca-12MgO for 80% of the application; with 20% applied before planting using solid granular fertilizers incorporated into the soil and combined with polymer doses; the remainder of the fertilizer was applied via irrigation water using soluble fertilizers: ammonium nitrate, monoammonium phosphate, potassium nitrate, calcium nitrate, potassium sulfate, and soluble micronutrients were added during the crop’s vegetative cycle, applied according to the crop’s nutrient requirements with weekly applications (Table a.19 through Table a.22) in the Appendix.

Shallow subsurface drip irrigation was used with a drip line in the center of the bed, at a nominal flow rate of 6.66 lph/m at a pressure of 10 psi; irrigation was performed twice a week (Mondays and Thursdays) from planting through head formation, and from head formation to maturity, irrigation was performed every third day. Irrigation rates were calculated based on potential evapotranspiration (ETo), which was determined from daily data recorded every 10 minutes by a Davis® weather station using the method of Hargreaves and Samani (1985), and the crop coefficient (Kc) was used to determine actual evapotranspiration (ETr) for the different stages of

lettuce growth, considering 100% and 75% of the crop's water requirement. The volume of water applied under each irrigation condition was 2.786 and 3.298 m^3/ha, respectively, for 75% and 100% of the water requirement (Table A.16 and Table A.17) in the Appendix. Soil moisture dynamics were recorded using tensiometers, and Figure a.6 in the Appendix shows their behavior under both water conditions.

Pest management was carried out using a preventive approach and weekly applications of the following chemical and biological products: Imidacloprid and Beta-cyhalothrin (300 ml/ha), Lambda-cyhalothrin (300 ml/ha), 1.0 kg/ha of BT (*Bacillus thuringiensis*), Imidacloprid (250 ml/ha), Spinosad (85 ml/ha), Imidacloprid and Beta-cyhalothrin (300 ml/ha), lambda-cyhalothrin (300 ml/ha), 1 kg/ha of BT (Bacillus thuringiensis), imidacloprid (250 ml/ha), and spinosad (85 ml/ha), using drones between 6:00 and 7:00 a.m.

On March 27, the first manual "pica" was performed; on April 13, mechanical weeding was carried out; and on April 14, the second manual "pica" was performed, removing the topsoil and weeds to allow for aeration of the root system and promote crop growth and development. Wire fencing was installed around the perimeter on March 20 to prevent damage from rodents and lagomorphs. Plant height was assessed at two time points, 28 and 50 days after transplanting (April 7 and 29); fresh weight and dry matter were measured 42 and 58 days after transplanting (April 21 and May 5–6); and relative water content was measured 45 days after transplanting (April 24). Yield and its components were assessed on May 5 and 6.

To analyze the fixed effects—which correspond to overall trends—and the random effects—which refer to variability among groups—mixed linear models were used, as they combine both and serve as a tool for interpreting interactions among the factors under study (Invierno, 2013).

The experiment was conducted using a split-split-plot design arranged in completely randomized blocks with four replications. The

main plot corresponded to the irrigation factor (100% and 75% of water requirement), while the subplots consisted of a factorial arrangement of fertilization levels (100% and 80%) and polymer doses (0, 18, 36, and 52 kg/ha).

To analyze the data on plant height (APDES), relative water content (RWC), and polar diameter (PD), linear mixed models (LMMs) were used via the lme4 package in the statistical software R (R Core Team, 2026). The management factors (irrigation, fertilization, and polymer), along with all their two-way and three-way interactions, were modeled as fixed effects.

The random effects structure was specified to accurately reflect the randomization constraints inherent in the experimental design and to control for sources of spatial variation. The random block effect (rep) was included to account for environmental variability across replicates. Additionally, an error term for the main plot was incorporated via the random interaction between the block and irrigation (rep:irrigation). This random intercept allowed for correction of the variance structure due to the clustering of subplots within the same irrigation plot, thereby avoiding the pseudo-replication error and ensuring a robust and unbiased estimate of the degrees of freedom and p-values for the main factor. The significance of the fixed effects was determined using Satterthwaite's approximation for degrees of freedom via the lmerTest package (R Core Team, 2026).

The variables evaluated were: APDES: Plant height during development (cm); APFC: Plant height during the growth phase (cm); MSD: Dry matter during development (t/ha); PMSD: Percentage of dry matter during development (%); CRA: Relative water content (%); NPHA: Number of plants per hectare;

PAGUA: Water productivity (kg/m^3); UEFN: Efficient use of nitrogen fertilizer (kg/kg); UEFP: Efficient use of phosphorus fertilizer (kg/kg); UEFK: Efficient use of potassium fertilizer (kg/kg); UEFCa: Efficient use of calcium fertilizer (kg/kg); UEFMg: Efficient use of magnesium fertilizer (kg/kg); DP: Polar diameter (cm); DP: Equatorial diameter (cm); PPPC: Average weight per head (g). CABCOS:

Number of heads harvested; PMSC:

Percentage of dry matter at harvest (%); CAC: Water content at harvest (%); MSC: Dry matter at harvest (t/ha); TGDE: Large head size; MSC: Dry matter at harvest (t/ha); TGDE: Large head size; TMED: Medium head size; TCHI: Small head size.

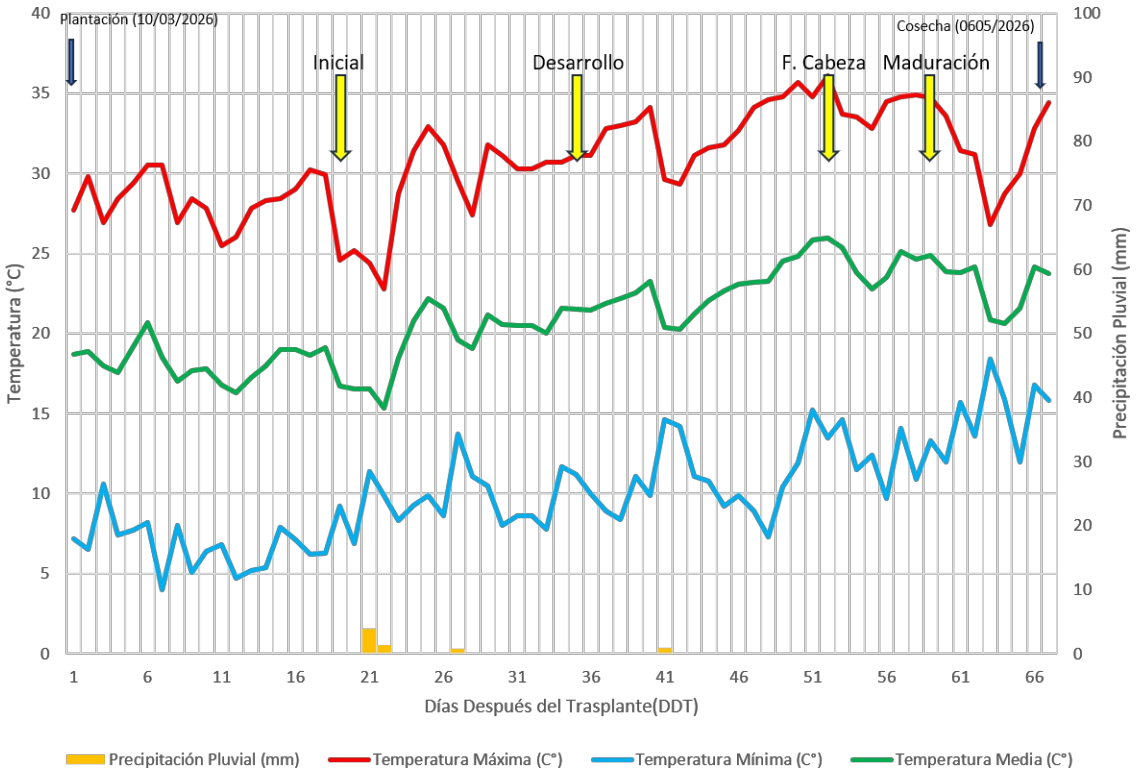


Figure 1. Phenological stages and trends in maximum, minimum, and average temperature, as well as rainfall, recorded at the Pabellón Experimental Field during the 2026 growing season.

RESULTS

Weather Conditions

Figure 1 shows temperature conditions and daily rainfall from March through May 2026, the period during which the lettuce crop was grown from planting through harvest. During this stage, minimum temperatures ranged from 5°C to 10°C and maximum temperatures from 25°C to 30°C; in contrast, during the phenological phase of

development, minimum temperatures ranged from 5°C to 15°C and maximum temperatures from 25°C to 30°C; during the head formation phase, only the maximum temperature increased, ranging from 30°C to 35°C, and in the final phenological phase, this temperature showed a downward trend toward 30°C. With regard to rainfall, precipitation occurred only around 21, 26, and 40 days after transplanting (ddt), with a cumulative rainfall of approximately 7.0 mm, a value very close to the historical average for March and April, which is 10 mm (Medina *et al*., 2006).

Agronomic Data

Before performing the analysis of variance (ANOVA), normality tests (Shapiro-Wilk) were conducted to ensure that the data followed a normal distribution, and tests for homogeneity of variance (Levene) were performed to ensure that the groups were comparable and the results were reliable. Table 1 shows the results, which indicate that most of the evaluated variables met these two conditions; for normality, the exceptions were NPHA, PMSC, CAC, TGDE, and TCHI; and for homogeneity of variance, only the TGDE variable did not meet this condition.

The ANOVA was performed using a split-plot design, where the main plot corresponds to the irrigation factor, the mid-plot to the fertilization factor, and the subplot to the polymer factor. Table 2 shows the mean squares and the level of statistical significance for the aforementioned variables, revealing a highly significant difference ($p < 0.01$) for the repetition effect on the APDES variable and a significant difference ($p < 0.05$) for the three-way interaction PolxIrrigationxFert; Similarly, a significant difference ($p < 0.05$) was detected for this same interaction in the CRA variable. For the RDTO variable, significant differences ($p < 0.05$) were detected for the main effects of Irrigation and Fertilization, while for PAGUA, significant differences ($p < 0.05$) were found in the replication and in the main effect of Irrigation.

Table 1. Normality (Shapiro–Wilk) and homogeneity of variance tests for the variables evaluated in the lettuce crop at Experimental Field Pavilion 2026.

Variable	Normality (Shapiro–Wilk)		Homogeneity of Variance (Levens)		
	W	p-value	DF	F-value	Pr(>F)
APDES	0.97854	0.328	15(48)	1.0731	0.4046
APFC	0.98926	0.8537	15(48)	0.7534	0.7191
MSD	0.98431	0.5917	15(48)	1.7545	0.07134
PMSD	0.97977	0.3753	15(48)	0.9296	0.5931
CRA	0.96662	0.07658	15(48)	0.7866	0.6855
NPHA	0.95639	0.02388	15(48)	0.8746	0.5949
RDTO	0.98015	0.3912	15(48)	0.4392	0.9582
PAGUA	0.98294	0.5203	15(48)	0.4651	0.9468
UEFN	0.98681	0.7282	15(48)	0.6098	0.8523
UEFP	0.98681	0.7282	15(48)	0.6095	0.8525
UEFK	0.98681	0.7283	15(48)	0.698	0.8523
UEFCa	0.9868	0.7277	15(48)	0.6097	0.8524
UEFMg	0.98679	0.7273	15(48)	0.6112	0.8511
DP	0.9869	0.7333	15(48)	0.8527	0.6453
DE	0.98796	0.7897	15(48)	1.0892	0.3907
PPPC	0.98401	0.5756	15(48)	0.6141	0.8488
CABCOS	0.9838	0.5649	15(48)	1.1657	0.5649
PMSC	0.94086	0.00416	15(48)	0.8607	0.6091
CAC	0.54086	0.00416	15(48)	0.8607	0.6091
MSC	0.8645	4.6E-06	15(48)	0.6904	0.7808
TGDE	0.95163	0.01137	15(48)	2.1897	0.02048
TMED	0.96541	0.06967	15(48)	1.7601	0.07023
TCHI	0.81228	1.4E-06	15(48)	0.543	0.9021

APDES: Height of developing plants (cm); APFC: Height of plants during the growth phase (cm); MSD: Developing dry matter (t/ha); PMSD: Percentage of developing dry matter (%); CRA: Relative water content (%); NPHA: Number of plants per hectare; PAGUA: Water productivity ($^{kg/m^3}$); UEFN: Efficient use of nitrogen fertilizer (kg/kg); UEFP: Efficient use of phosphorus fertilizer (kg/kg); UEFK: Efficient use of potassium fertilizer (kg/kg); UEFCa: Efficient use of calcium fertilizer (kg/kg); UEFMg: Efficient use of magnesium fertilizer (kg/kg); DP: Polar diameter (cm); DP: Equatorial diameter (cm); PPPC: Average weight per head (g). CABCOS: Number of heads harvested; PMSC: Percent dry matter at harvest (%); CAC: Water content at harvest (%); MSC: Dry matter at harvest (t/ha); TGDE: Large-sized MSC: Dry matter at harvest (t/ha); TGDE: Large head size; TMED: Medium head size; TCHI: Small head size.

Table 2. ANOVA and significance level for the variables evaluated in lettuce, Experimental Field Pavilion 2026.

Source of Variation	G.L.	APDES	APFC	MSD	PMSD	CRA	NPHA	RDTO	PAGUA
REP	3	4.4408**	0.211	0.011719	0.17235	11.346	23,433,665	147.75	18.564*
IRRIGATION	1	6.0025	4.7306	0.039502	0.54409	2.192	30,862,191	2,682.02*	7.118
Ea	3	1.2633	1.0394	0.011169	0.31222	32,957	7,429,144	106.46	14.072
FERT	1	0.5256	0.0156	0.021756	0.95526	1.306	30,862,191	414.39*	51.06*
IRRIGATION:FERT	1	0.0006	0.5256	0.032942	0.01792	3.871	13,714,986	212.88	29.134
Eb	6	0.2965	0.8735	0.043954	0.43406	15.591	22,289,361	51.27	5.402
POL	3	2.1071	0.5035	0.005091	0.05719	7.761	3,429,132	89.82	8.946
POL:IRRIGATION	3	0.7146	2.7802	0.006946	0.02654	20.886	11,430,853	43.08	3.859
POL:FERT	3	0.546	1.1235	0.016995	0.16626	24.557	70,873,571	33.51	3.683
POL:IRRIGATION:FERTILIZER	3	2,171*	0.6885	0.024791	0.02447	43.699*	24,005,779	51.96	5.691
Ec	36	0.7423	1.0662	0.016575	0.16204	12.224	30,864,120	53.11	5.764
C.V. (a)		11.5	6.5	8.7	10.6	7.4	3.6	15.9	17.6
C.V. (b)		5.6	5.9	17.3	12.4	5.1	6.2	11	10.9
C.V. (c)		8.8	6.6	10.6	7.6	4.5	7.3	11.2	11.2
Average		9.75	15.51	1.21	5.29	77.82	76,388.77	65.00	21.34

APDES: Height of developing plants (cm); APFC: Height of plants in the growth phase (cm); MSD: Developing dry matter (t/ha); PMSD: Percentage of developing dry matter (%); CRA: Relative water content (%); NPHA: Number of plants per hectare; PAGUA: Water productivity (kg/m^3).

* Significant difference at a probability level ≥ 0.05

** Significant difference at a probability level of ≥ 0.01

For the variables APEC, MSD, PMSD, and NPHA, no statistical difference was found for any of their components; the coefficients of variation ranged from 3.6% to 17.6% across the different variables and for the various factors

evaluated.

Table 2. Continued...

Source of Variation	G.L.	UEFN	UEFP	UEFK	UEFCa	UEFMg	DP	DE	PPPC
REP	3	16.11	6,079	38	0.5132	0.1851	2.6939**	4.8239**	31,857*
IRRIGATION	1	269.84*	101.826*	636.41*	8.6032*	3.0976*	4.5689	16.5039	119,008
Ea	3	9.35	3.527	22.04	0.2978	0.0107	1.6881	3.1131	15,123
FERT	1	654.64**	247.02**	1543.91**	20.8723**	7.5158**	1.9252*	11.4752**	121,749**
IRRIGATION:FERT	1	8.37	3.159	19.75	0.2672	0.0959	0.1502	0.1502	2.97E+03
Eb	6	4.7	1.775	11.08	0.15	0.0539	0.2793	0.6006	6209
POL	3	10.3	3.886	24.3	0.3286	0.1182	0.0568	0.5252	5811
POL:IRRIGATION	3	4.4	1.659	10.37	0.14	0.0505	0.9435	1.2968	4601
POL:FERT	3	4.34	1.637	10.23	0.1384	0.0498	1.7039*	0.3756	7,365
POL:IRRIGATION:FERT	3	5.34	2.014	12.59	0.1699	0.0613	0.5681	2.2539	14,564
Ec	36	6.49	2.45	15.32	0.2071	0.0745	0.5172	0.8798	8146
C.V. (a)		14.3	14.3	14.3	14.3	14.3	10.2	10.9	21.7
C.V. (b)		10.1	10.1	10.1	10.1	10.1	4.2	4.8	13.9
C.V. (c)		11.9	11.9	11.9	11.9	11.9	5.7	5.8	15.9
Average		21.38	13.13	32.83	3.82	2.29	12.72	16.18	566.43

UEFN: Efficient use of N fertilizer (kg/kg); UEFP: Efficient use of P fertilizer (kg/kg); UEFK: Efficient use of K fertilizer (kg/kg); UEFCa: Efficient use of Ca fertilizer (kg/kg); UEFMg: Efficient use of Mg fertilizer (kg/kg); DP: Polar diameter (cm); DP: Equatorial diameter (cm); PPPC: Average weight per head (g).

* Significant difference with a probability of ≥ 0.05

** Significant difference at a probability level of ≥ 0.01

To determine fertilizer productivity, the applied fertilization treatments were partitioned according to the percentage of each nutrient included in the lettuce crop fertilization and calculated based on fresh weight yield (RDTO). Thus, for the variables UEFN, UEFP, UEFK, UEFCa, and UEFMg (nitrogen, phosphorus, Potassium, Calcium, and Magnesium), significant differences ($p < 0.05$) were detected for the main factor IRRIGATION and highly significant differences ($p < 0.01$) for the factor FERT.

Table 2. Continued...

Source of Variation	G.L.	CABCOS	PMSC	CAC	MSC	TGDE	TMED	TCHI
REP	3	2448327	0.02511	0.02511	0.27942	8.104*	8.0417*	13.3542**
IRRIGATION	1	942566752*	2.96873	2.96873	0.79656	36,000	16.0000	4.0000
Ea	3	42064697	0.83494	0.83494	0.20776	4.292	3.4583	0.6250
FERT	1	390457600*	2.26126**	2.26126**	0.01925	20.25	12.2500	1.0000
IRRIGATION:FERT	1	167618336	1.10408*	1.10408*	0.00000	7.562	12.2500	0.5625
Eb	6	54421117	0.11166	0.11166	0.08944	4.573	4.0833	0.6563
POL	3	65786075	0.07153	0.07153	0.08016	2.604	2.7083	1.3542
POL:IRRIGATION	3	6,072,895	0.23318	0.23318	0.13522	3.792	2.0417	0.5417
POL:FERT	3	117360672	0.12061	0.12061	0.00093	2.625	2.7917	0.6250
FERTILIZER:IRRIGATION:FERT	3	59665005	0.06173	0.06173	0.02943	2.687	1.2917	1.9375
Ec	36	46282122	0.14688	0.14688	0.10516	2.788	2.3611	1.1007
C.V. (a)		10.50	25.2	0.9	19.6	46.4	42.5	68.4
C.V. (b)		11.90	9.2	0.3	12.8	47.9	46.2	70.1
C.V. (c)		11.00	10.6	0.4	13.9	37.4	35.1	90.7
Average		619,984.44	3,629	96,371	2.328125	4.46875	4.375	1.15625

CABCOS: Number of heads harvested; PMSC: Percent dry matter at harvest (%); CAC: Water content at harvest (%); MSC: Dry matter at harvest (t/ha); TGDE: Large head size; TMED: Medium head size; TCHI: Small head size
* Significant difference at a probability level ≥ 0.05
** Significant difference at a probability level of ≥ 0.01.

For the CABCOS variable, significant differences ($p < 0.05$) were detected in the main factors or effects IRRIGATION and FERT; for PMSC and CAC, statistically significant differences ($p < 0.05$) were found for the IRRIGATION × FERT interaction, whereas for the lettuce size variables (TGDE, TMED, and TCHI), there was only a statistical difference between replicates.

Table 3 shows the arithmetic mean of the 16 treatments evaluated with their respective combinations of the main factors under evaluation, derived from

field data and based on the response across the four replicates.

Table 3. Means by treatment for the variables evaluated in lettuce that showed a statistically significant difference. Experimental Field Pavilion 2026.

TREATMENT	IRRIGATION	FERT	POL	APDES	CRA	RDTO	PAGUA	UEFN	UEFP	UEFK
1	75%	80%	0	9.9	79,639	55.18	19,804	16,061	9,866	24,664
2	100%	80%	0	9,875	77,925	72,281	21,917	21,038	12,923	32,308
3	75%	100%	0	10.3	75,107	65,193	23,398	23,719	14.57	36,425
4	100%	100%	0	10.85	76,661	79,576	24.13	28,952	17,785	44,462
5	75%	80%	18.08	9.3	75.137	54.65	19,614	15,906	9,771	24,428
6	100%	80%	18.08	10,335	78.49	65,276	19,793	18,999	11,671	29,177
7	75%	100%	18.08	9.7	82.49	61,878	22,208	22,513	13,829	34,573
8	100%	100%	18.08	9.55	75,847	67,898	20,589	24,703	15,175	37,937
9	75%	80%	36.08	9.1	73,881	57.14	20,508	16,631	10,216	25,541
10	100%	80%	36.08	10.25	78.43	72.058	21.85	20.973	12,884	32,209
11	75%	100%	36.08	9,775	76,926	60,617	21,756	22,054	13,547	33,868
12	100%	100%	36.08	9,675	79,672	71,722	21,748	26,094	16,029	40,073
13	75%	80%	52.8	9.1	80,334	49,681	17,831	14.46	8,883	22,207
14	100%	80%	52.8	9,425	77,594	73,416	22,262	21,368	13,126	32,816
15	75%	100%	52.8	8,375	77,578	63,911	22,938	23,252	14,284	35,709
16	100%	100%	52.8	10.5	79,434	69.6	21,105	25,322	15,555	38,888

TREAT: Treatment evaluated; REP: Replication; IRR: Irrigation level evaluated; FERT: Fertilization level evaluated; POL: Polymer dose evaluated; APDES: Plant height during growth (cm); CRA: Relative water content (%); RDTO: Fresh weight at harvest (t/ha); PAGUA: Water productivity (kg/m^3); UEFN: Efficient use of nitrogen fertilizer (kg/kg); UEFP: Efficient use of (kg/kg); UEFK: Efficient use of potassium fertilizer (kg/kg).

Triple interaction: Irrigation × Fertilization × Polymer

Plant height during the phenological development stage (APDES). Figure 2 shows the behavior of the four polymer rates; at the 0 kg/ha polymer rate (Figure 2a), a positive trend toward increased plant height is observed as fertilization increases from 80% to 100% under both irrigation conditions (75% and 100% of the crop's water requirements), and within these irrigation levels, an increase in plant height of approximately 0.55 cm is observed; whereas for the 18.08 kg/ha polymer dose (Figure 2b), there is a positive response to the irrigation factor, which, when combined with increased fertilization, results in a plant height increase of

0.4 cm; in contrast, at the 100% irrigation rate, plant height decreases by -0.47 cm as fertilization increases; for the 36.08 kg/ha dose (Figure 2c), a trend similar to the previous dose was observed, with the following magnitudes: 0.68 cm for the 75% irrigation treatment and -0.57 cm for the 100% irrigation treatment as lettuce fertilization was increased; and for the 52.80 kg/ha polymer dose (Figure 2d), plant height increased under the 100% irrigation requirement condition when fertilization was raised from 80% to 100%, with an increase of 1.07 cm, whereas when only 75% of the lettuce's irrigation requirement was applied, an increase in fertilization resulted in a decrease of -0.72 cm; at this polymer dose, the greatest absolute changes in this variable occurred when the two factors—irrigation and fertilization—were combined.

Table 3. Continued...

TREATMENT	IRRIGATION	FERT	POL	UEFCa	UEFMg	DP	DE	PPPC	CABCOS	PMSC
1	75%	80%	0	2,868	1,721	12,175	15,375	495,025	54,971	4,114
2	100%	80%	0	3,757	2,254	12.1	16,075	554.15	66,565	3,574
3	75%	100%	0	4,235	2,541	13.35	15,775	607,625	64,642	3,398
4	100%	100%	0	5.17	3.102	13.55	17.7	721,025	69,266	3,115
5	75%	80%	18.08	2.84	1,704	12.6	16.2	518,725	54,421	4,019
6	100%	80%	18.08	3,393	2,036	12.85	15.5	560,675	63,907	3,523
7	75%	100%	18.08	4.02	2,412	12,275	15,725	539.85	56,295	3,392
8	100%	100%	18.08	4,411	2,647	12,975	16.75	626,375	64,645	3,466
9	75%	80%	36.08	2.97	1,782	12.4	14,975	489.8	60,321	4,241
10	100%	80%	36.08	3,745	2,247	12,925	16,875	551,925	66,601	3,255
11	75%	100%	36.08	3,938	2,363	12.7	16.6	554,375	60,806	3,859
12	100%	100%	36.08	4.66	2,796	12.95	17,225	612.9	66,516	3,302
13	75%	80%	52.8	2,582	1,549	11.75	14.65	387,975	46,530	4.28
14	100%	80%	52.8	3,816	2,289	13,575	16,425	624.25	62,817	3,529
15	75%	100%	52.8	4,152	2,491	12,375	16.1	593.1	67,205	3.45
16	100%	100%	52.8	4,522	2,713	12,975	16,975	625,125	66,276	3,544

TREAT: Treatment evaluated; REP: Replication; IRRIGATION: Irrigation level evaluated; FERT: Fertilization level evaluated; POL: Polymer dose evaluated; UEFCa: Efficient use of calcium fertilizer (kg/kg); UEFMg: Efficient use of magnesium fertilizer (kg/kg); DP: Polar diameter (cm); DP: Equatorial diameter (cm); PPPC: Average weight per head (g). CABCOS: Number of heads harvested; PMSC: Percent dry matter at harvest.

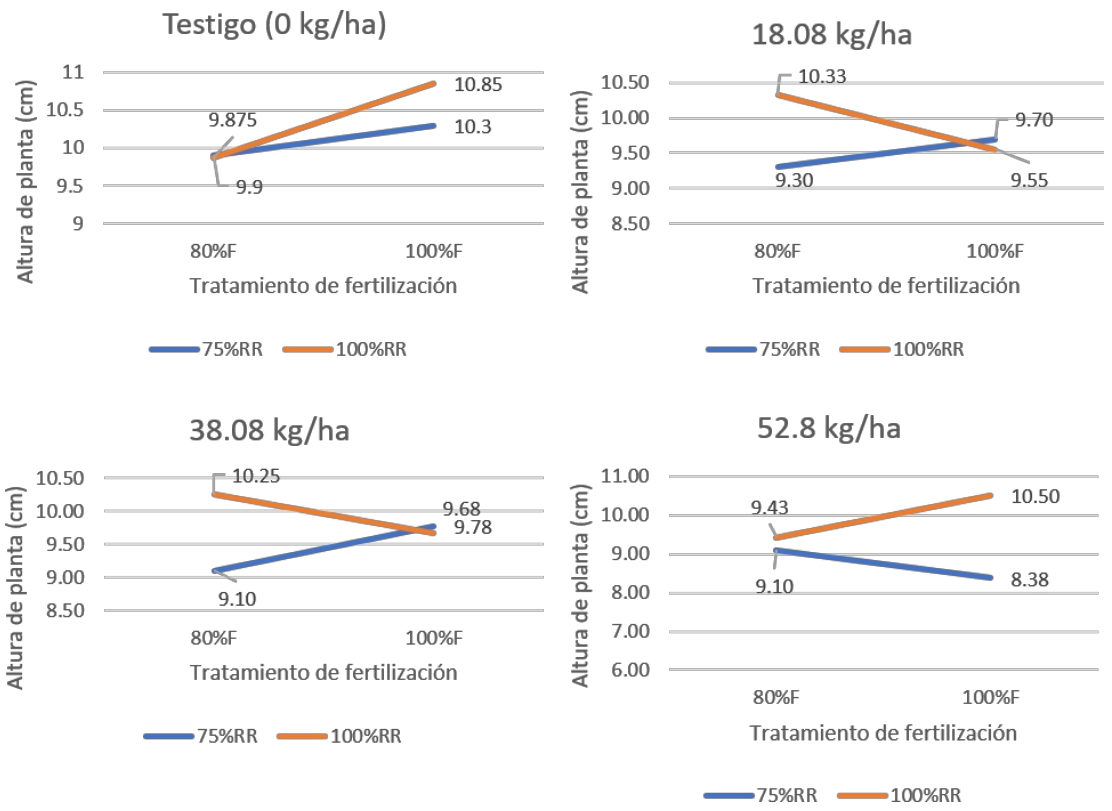


Figure 2. Plant height during the phenological development stage of lettuce under different doses of an organic polymer, with two levels of irrigation and fertilization. Pabellón Experimental Field. 2026.

The Duncan's multiple range test ($p < 0.05$) is presented in Table 4, which shows that the treatment with the greatest plant height was that receiving 100% of the irrigation requirement, 100% of the fertilizer requirement, and 0 kg/ha of polymer, with a height of 10.85 cm; however, this height was statistically equivalent to nine of the 16 treatments, which indicates that for this variable, the application of the polymer did not have a significant effect. This may be related to the water-holding capacity of the soil where the experiment was conducted; at the time of sampling, although the polymer increased moisture retention by 0.54%, the crop did not utilize this moisture because there was no significant depletion of soil moisture.

Table 4. Test of means and their significance for plant height during development (APDES) in its three-way interaction in the lettuce crop. Pabellón Experimental Field. 2026.

Irrigation	Fert	Polymer	APDES*
100%RR	100%F	0 kg/ha	10,850 a
100%RR	100%F	52.8 kg/ha	10,500 ab
100%RR	80%F	18.08 kg/ha	10,325 abc
75%RR	100%F	0 kg/ha	10,300 abc
100%RR	80%F	36.08 kg/ha	10,250 abc
75%RR	80%F	0 kg/ha	9,900 abc
100%RR	80%F	0 kg/ha	9,875 abc
100%RR	100%F	36.08 kg/ha	9,775 abc
75%RR	100%F	18.08 kg/ha	9,700 abc
100%RR	100%F	36.08 kg/ha	9,675 abc
100%RR	100%F	18.08 kg/ha	9,550 bcd
100%RR	80%F	52.8 kg/ha	9,425 bcd
75%RR	80%F	18.08 kg/ha	9,300 bcd
75%RR	80%F	36.08 kg/ha	9,100 cd
75%RR	80%F	52.8 kg/ha	9,100 cd
75%RR	100%F	52.8 kg/ha	8,375 d

*Treatments with the same letter are statistically equivalent with a probability of P ≥ 0.05 (MSD = 2.234).

Using mixed linear models (Table a.1. in the Appendix), the baseline condition (intercept) for plant height during development (APDES) was determined. The results indicate that plants under the initial condition (75% + 80% fertilizer + 0 kg/ha of polymer) have an average height of 9.90 cm; this is the only statistically significant value ($p < 0.001$), which validates this starting point.

The impact of the individual factors (main effects) is as follows: as irrigation increases (to 100% of the crop's water requirement), plant height decreases non-significantly by 0.025 cm ($p = 0.968$); whereas increasing fertilization to 100% increases plant height by 0.40 cm, but there is also no statistically significant difference ($p = 0.496$), and for the use

The application of the polymer at any rate (18.08, 36.08, or 52.20 kg/ha) tends to slightly reduce plant height (between -0.60 and -0.80 cm) compared to the control (0 kg/ha), but these reductions are not significant either ($p > 0.17$).

Interactions (combined effects), which include two-way and three-way interactions, allow for an evaluation of the polymer's biological effectiveness when applied in conjunction with 100% of the irrigation or fertilization. The results indicated that no interaction is significant; that is, combining the treatments does not result in a differential change in plant height during the phenological development phase of lettuce.

Based on the above, during the phenological development phase, the height of the lettuce crop is very stable; it does not respond to increases in water (from 75% to 100%), fertilizer (from 80% to 100%), or the addition of polymer at any of its doses. From an input-saving perspective, at this specific stage, the lowest-input treatment (75% Irrigation + 80% Fertilizer + 0 kg/ha polymer) yields virtually the same plant height as the options requiring greater investment.

Relative Water Content (RWC). Figure 3 shows the integration of this variable with the three factors (irrigation, fertilization, and polymer), revealing that for the control treatment (0 kg/ha) of polymer (Figure 3a), under both irrigation conditions; for the 75% treatment, there is a tendency for the RWC to decrease as fertilization increases from 80% to 100%, with RWC values ranging from 79.64% to 75.21%, whereas the decrease in this variable under the 100% irrigation condition ranged from 77.92% to 76.66% CRA, suggesting that in the absence of polymer, this variable is affected by fertilizer application—likely due to an increase in osmotic pressure that impairs water uptake in the lettuce root system.

When analyzing the behavior of the polymer dose of 18.08 kg/ha (Figure 3b) and the Irrigation × Fertilizer × Polymer interaction, it is observed that under the irrigation condition of 75% of the lettuce's water requirements, the CRA is

75.14%

with the 80% fertilization treatment; and under this irrigation condition, when fertilization was increased to 100%, an increase in the crop's CRA is observed, possibly due to the polymer's role in water supply and increased nutrient availability, which promoted greater tissue hydration at the cellular level, causing the CRA to rise from 75.14% to 82.49%; the opposite occurred with the 100% requirement treatment, since moving from lower to higher fertilization—and with this polymer dose—affected the CRA, which decreased from 78.49% to 75.85%.

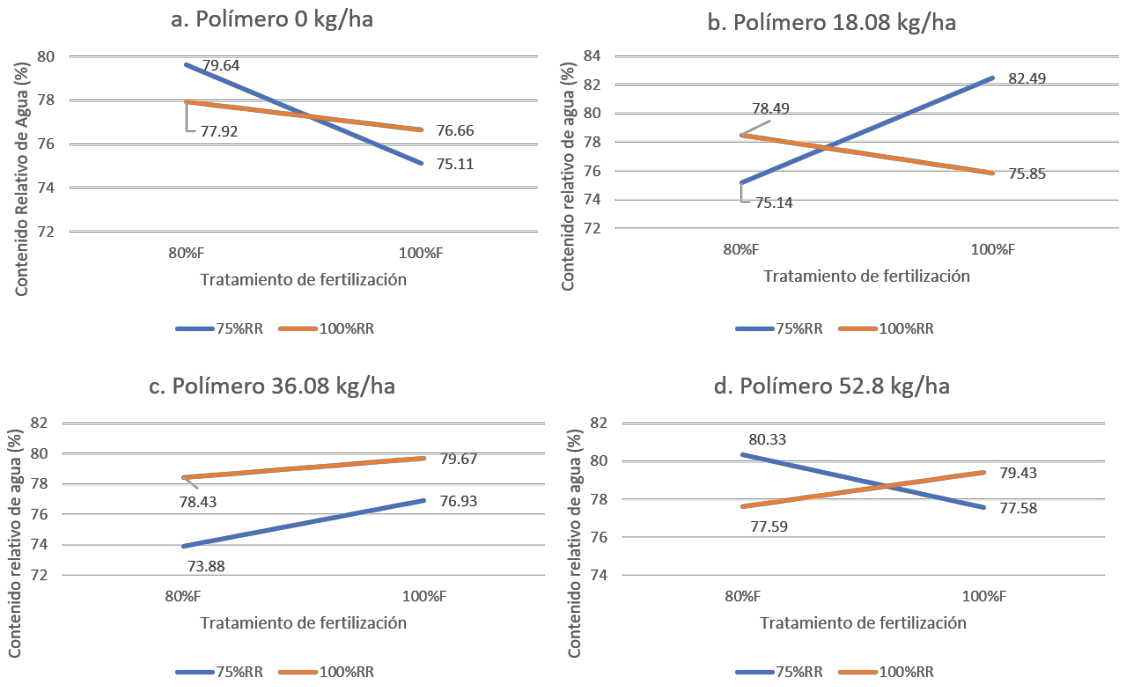


Figure 3. Relative water content during the development phase (CRA) in a lettuce crop with four polymer doses and under two levels of fertilization and irrigation. Pabellón Experimental Field. 2026.

When observing the trend lines for the polymer dose of 36.08 kg/ha (Figure 3c), a positive linear trend is observed under both irrigation conditions; however, the 100% irrigation treatment showed a CRA of 78.43% at 80% fertilization and 79.67% at 100% fertilization; whereas for the 75% irrigation condition, combined with 80% fertilization, the CRA

was 73.88% and increased to 76.93% as fertilization was increased. Therefore, it can be concluded that at this polymer dose, there is an almost linear positive trend in CRA behavior, since higher irrigation and higher fertilization lead to increased relative water content in the plant.

In the case of the highest polymer dose at 52.80 kg/ha (Figure 3d), the trend is a decrease in CRA under the 75% irrigation condition as crop fertilization increases from 80% to 100%, with values of 80.33% and 77.58%, respectively. This suggests that, at this polymer dose, fertilization affects the water status of the lettuce; whereas for the 100% irrigation condition, the CRA values were 77.59% and 79.43% for 80% and 100% fertilization, respectively; that is, fertilization and the polymer promote crop hydration.

Tukey's test of means ($p < 0.05$) revealed that the best treatment in the irrigation × fertilization × polymer combination was 75% × 100% × 18.08 kg/ha of polymer, with a CRA of 82.49%, as it exhibited the highest water content in the plant, although it was statistically equivalent to nine other treatments and/or combinations. Meanwhile, the treatment of 75% × 80% × 36.08 kg/ha of polymer had the lowest RWC value at 73.88% (Table 5).

Using mixed linear models (Table a.2) in the Appendix, the behavior of the Relative Water Content (RWC)—which measures the plant's water status—was analyzed. This analysis revealed a significant three-way interaction, indicating that the effect of the polymer changes completely depending on the amount of irrigation and fertilizer applied to the crop. Under the baseline condition (intercept) for this variable, the results indicate that plants under the initial condition—or those under optimal management (100% Irrigation + 100% Fertilizer + 0 kg/ha of Polymer)—maintain an average RWC of 76.66%.

The key finding of the study was the three-way interaction (Irrigation 75%: Fertilizer 80%: Polymer 18.08 kg/ha) with a strongly negative coefficient (p = 0.0110), which can be interpreted as follows: when stress conditions are combined (75% Irrigation and 80% Fertilization along with a dose of 18.08 kg/ha), the plant's CRA drops drastically by 13.26% compared to what would be expected; which, from an agronomic standpoint, means that under conditions of dual limitation (water and nutrients), a low polymer dose (18.08 kg/ha) is insufficient to protect the plant; on the contrary, under this model, it exhibits the worst water performance. However, the higher doses (36.08 and 52.80 kg/ha) manage to mitigate this drop in water content, as their three-way interactions are not significantly negative.

Table 5. Test of means and their significance for relative water content (RWC) in its three-way interaction in lettuce cultivation. Pabellón Experimental Field. 2026.

IRRIGATION	FERT	POL	RWC	Means
75	100	18.08	82,490	to
75	80	52.8	80,334	ab
100	100	36.08	79,672	abc
75	80	0	79,639	abc
100	100	52.8	79,434	abc
100	80	18.08	78,490	abcd
100	80	36.08	78,430	abcd
100	80	0	77,925	abcd
100	80	52.8	77,594	abcd
75	100	52.8	77.578	abcd
75	100	36.08	76,926	bcd
100	100	0	76,662	bcd
100	100	18.08	75,847	bcd
75	80	18.08	75,138	cd
75	100	0	75.107	CD
75	80	36.08	73,881	d

*Treatments with the same letter are statistically equivalent with a probability of P ≥ 0.05 (MSD = 2.234).

Two-way interaction: Fertilization × Polymer

Polar diameter (PD). The Fertilization × Polymer interaction is shown in Figure 4, which displays the various polymer doses evaluated. A general graphical analysis of the trend reveals that PD is affected by the fertilization level; specifically, with the application of 80% of the recommended fertilization rate—and when moving from the control (0 kg/ha) to 18.08 kg/ha— the polar diameter increases from 12.14 to 12.73 cm and subsequently remains constant or without significant changes at higher polymer doses; whereas, for the treatment with 100% fertilization and an increase in polymer from 0 to 18.06 kg/ha, the PD decreases from 13.45 to 12.63 cm, while at the highest polymer doses, the PD remains nearly constant.

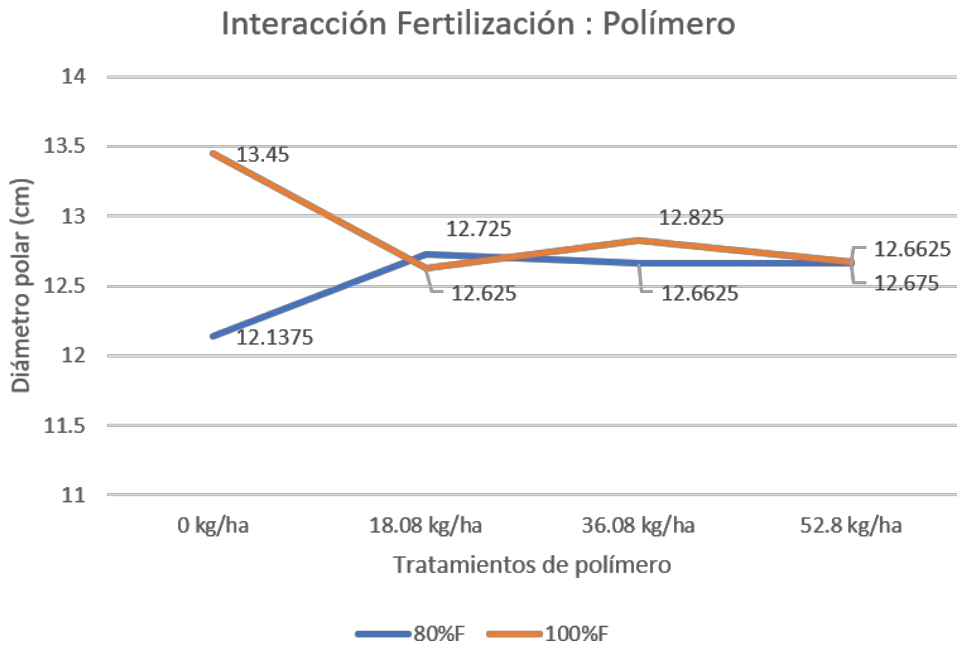


Figure 5. Polar diameter (PD, cm) for the Fertilization × Polymer interaction in lettuce cultivation. Pabellón Experimental Field. 2026.

Based on Tukey's test of means ($p < 0.05$), Table 6 shows that the combination with the highest DP corresponds to the treatments that included 100% fertilization with the control polymer (0 kg/ha) and 36.08 kg/ha,

with 13.45 and 12.83 cm, respectively, and were statistically similar; furthermore, this latter dose is statistically equivalent to the 80% fertilization treatment at a dose of 18.08 kg/ha, which yielded 12.73 cm.

Table 6. Test of means and their significance for Polar Diameter (PD) in the double interaction of fertilization × polymer in lettuce cultivation. Pabellón Experimental Field. 2026.

Fert	Polymer	PD (cm)
100%F	0 kg/ha	13.4500 a
100%F	36.08 kg/ha	12.8250 ab
80%F	18.08 kg/ha	12.7250 bc
100%F	52.8 kg/ha	12.6750 bc
80%F	36.08 kg/ha	12.6625 bc
80%F	52.8 kg/ha	12.6625 bc
100%F	18.08 kg/ha	12.6250 bc
80%F	0 kg/ha	12.1375 c

*Treatments with the same letter are statistically equivalent with a probability of P ≥ 0.05 (MSD = 1.144).

Using the statistical tool of mixed linear models (Table A.3) in the Appendix, it was determined that, for DP, no significant three-way interactions were detected; however, it was found that 80% fertilization drastically alters how the plant responds to the polymer. The baseline condition (intercept) for this variable (100% Irrigation + 100% Fertilization + 0 kg/ha of Polymer) indicates that plants under this initial condition have an average polar diameter of 13.55 cm.

The effect of fertilization (80% Fert) was highly significant (p = 0.00518), which is interpreted as follows: reducing fertilization to 80% (while maintaining irrigation at

100% and without polymer) directly reduces the polar diameter by -1.45 cm. The nutrient deficit severely inhibits cellular growth of the diameter. The key finding is that the polymer demonstrates a synergistic effect that optimizes nutrient use efficiency, mitigating the nutritional deficit in lettuce cultivation; here, a visually clear phenomenon occurs in the two-way interactions (80% Fertilization : 36.08 kg/ha Polymer) with a statistically significant increase in DP of 1.4125 cm ($p = 0.04665$), and in the interaction (80% Fertilization : 52.80 kg/ha Polymer), the DP increases by 2.05 cm, which is highly significant ($p = 0.00519$).

When interpreting these results, it can be concluded that when the plant is experiencing nutrient deficiency (Fert 80%), the application of high doses of polymer (36.08 and especially 52.80 kg/ha) reverses the negative effect of low nutrient availability. From an agronomic standpoint, this response can be explained by the fact that when 52.08 kg/ha of polymer is applied under 80% fertilization, the diameter not only recovers the 1.45 cm lost but also increases the net diameter. This suggests that the polymer improves the efficiency of nutrient uptake from the soil by retaining more moisture around the roots.

Effect of Treatments on RWC and DB

Analysis of Relative Water Content (RWC) revealed a significant three-way interaction among the factors of irrigation, fertilization, and polymer dose ($F = -13.265$, $p = 0.0110$). Under conditions of dual input limitation (75% irrigation and 80% fertilization), the application of the lowest polymer dose (18.08 kg/ha) induced a severe and statistically significant 13.26% reduction in RWC compared to the optimal control (100% irrigation, 100% fertilizer, 0 kg/ha). In contrast, increasing the polymer dose to 36.08 and 52.80 kg/ha mitigated this water loss, stabilizing CRA values at levels similar to the baseline condition (76.66%).

With regard to DP, no third-order interactions were observed; however, a detrimental main effect was identified, as reducing fertilization to 80% decreased DP by 1.45 cm, which was highly significant ($p = 0.0051$). Nevertheless, this negative impact was significantly reversed through two-way interactions when medium and high doses of polymer were incorporated. Specifically, the combinations of 80% fertilization with 36.08 and 52.80 kg/ha significantly increased DP by 1.425 cm ($p = 0.0466$) and by 2.050 cm in a highly significant manner ($p = 0.0051$), which may have compensated for the nutritional deficit, promoting a net increase in polar diameter.

The absence of significant changes in plant height during the phenological development phase (APDES) suggests that the crop's longitudinal growth exhibits a high degree of homeostasis in response to the evaluated water and nutritional variations. However, the physiological and histological variables CRA and DP demonstrated critical sensitivity to the combined treatments.

The drastic drop in CRA observed when combining deficit management (75% irrigation and 80% fertilization) with a polymer dose of 18.08 kg/ha indicates that insufficient polymer applications under severe stress conditions are counterproductive, possibly due to transient competition for available water between the unsaturated polymer matrix and the root system. This phenomenon of water destabilization disappears when the dose is increased to
36.08 kg/ha, the threshold at which the polymer achieves the retention capacity necessary to mitigate the soil water deficit.

Furthermore, the ability of the 36.08 and 52.80 kg/ha application rates to reverse the loss of polar diameter under 80% fertilization indicates an increase in nutrient use efficiency (NUE). The literature indicates that water-absorbing polymers not only retain water but also capture and gradually release fertilizer ions, reducing their leaching in the soil profile. By maintaining an optimally moist root zone, mass flow and diffusion are stimulated, facilitating

the plant to absorb limiting nutrients and sustain cell growth, as reflected in the polar diameter.

Double Interaction: Irrigation × Fertilization

The variables—percent dry matter at harvest (PMSC) and water content at harvest (CAC)—proved statistically significant in their Irrigation × Fertilization interaction. These variables are complementary because, according to the physiological characteristics of lettuce, its growth depends primarily on cell expansion driven by water absorption and the maintenance of cell turgor. According to Taiz *et al*. (2018), the increase in cell volume through water accumulation in vacuoles is one of the most efficient mechanisms for increasing fresh biomass without requiring a high metabolic investment in the synthesis of structural compounds. As a result, a large proportion of the plant's weight consists of water stored in the tissues.

Percentage of Dry Matter at Harvest (PMSC)

Figure 5a shows the interaction between irrigation and fertilization on the DFHV variable, where the treatment with 75% of the irrigation requirement and 80% of the fertilization yielded 4.164%, and upon increasing fertilization to 100%, there was a decrease in dry matter accumulation to 3.525%, which is consistent with Taiz *et al*., (2018), since cell expansion is energetically more efficient than the formation of new carbon-rich structural tissues; thus, the plant tends to increase cell volume before dry matter density; whereas under the 100% water requirement condition, there were no significant increases in biomass accumulation, which ranged from 3,470 to 3,357 percent; therefore, under this irrigation condition, the fertilization treatment did not influence the behavior of PMSC.

The mixed linear model for dry matter content at harvest (Table A.4) in the Appendix shows that its behavior was not significantly influenced by the applied polymer doses ($p > 0.05$). Under the

base treatment conditions (75% irrigation, 80% fertilization, and 0 kg/ha of polymer), the model estimated an initial dry matter value of 3.12% (EE = 0.211) ($p < 0.001$). The variations observed when incorporating 18 kg/ha ($p = 0.1953$), 36 kg/ha ($p = 0.4870$), and 52 kg/ha of polymer ($p = 0.1149$) were statistically insignificant, indicating that this polymer does not alter dry biomass accumulation in the crop under the evaluated water and nutrient regimen, under these experimental conditions.

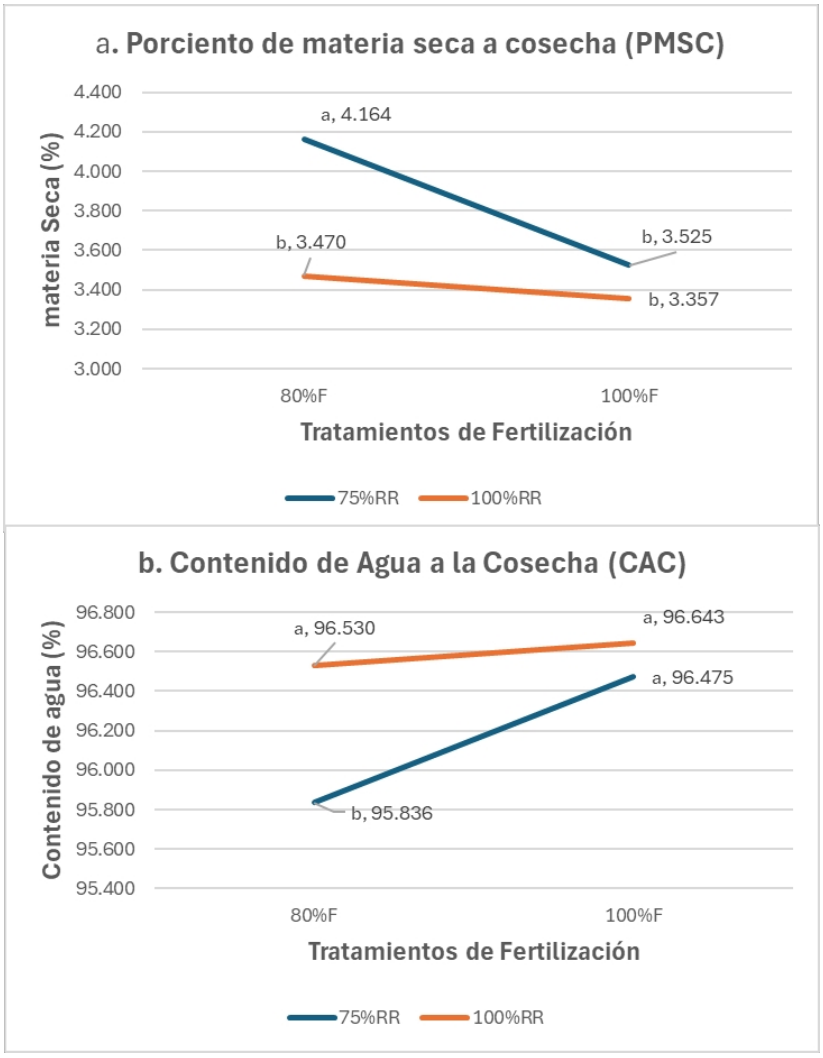


Figure 5. Trends in the percentage of dry matter at harvest (PMSAC) and water content at harvest (CAC) for the Irrigation × Fertilizer interaction in the lettuce crop. Pabellón Experimental Field. 2026.

Water Content at Harvest (CAC)

Figure 5b shows the water content at harvest (CAC), where the treatment with 100% of the irrigation requirement exhibited the highest values at 96.530% and 96.643% for 80% and 100% fertilization, respectively, which were statistically equivalent according to Tukey's mean separation ($P \geq 0.05$); whereas for the 75% irrigation requirement condition, the WHC ranged from 95.836% to 96.475% for 80% and 100% fertilization, respectively, and these values were statistically different according to the mean comparison test performed, which indicates that when water supply is restricted in lettuce, fertilization influences the water content at harvest, a consequence of various physiological processes related to growth, cell expansion, and the anatomical composition of leaf tissues (Santos *et al*., 2021; Rouphael and Colla, 2020).

The mixed linear model for CAC (Table a.4) in the Appendix shows that its behavior was not significantly influenced by the applied polymer doses ($p > 0.05$). Under the control treatment conditions (75% irrigation, 80% fertilization, and 0 kg/ha of polymer), the model estimated an initial water content of 95.89% (EE = 0.211) ($p < 0.001$). The variations observed when incorporating 18.08 kg/ha ($p = 0.72$), 36.08 kg/ha ($p = 0.64$), and 52.80 kg/ha of polymer ($p = 0.54$) were statistically insignificant, indicating that this polymer does not alter the plant's water content under the evaluated water and nutrient regimen.

Main Effects

The response of the lettuce crop to the main factors of irrigation and fertilization is based on the fact that it is a leafy vegetable that stores more than 95% water (fresh weight) in its plant tissues; therefore, there is a direct relationship between the level of water supply and the fertilization applied at the experimental site, in loamy soil with low fertility; with low nitrogen levels (4.47 ppm), moderately low phosphorus (13.5 ppm), moderately high potassium (552 ppm), medium

calcium availability (2,220 ppm), moderately low in magnesium (164 ppm), and with levels of the micronutrients iron, zinc, manganese, and copper ranging from moderately low to low (Fertilab, 2026).

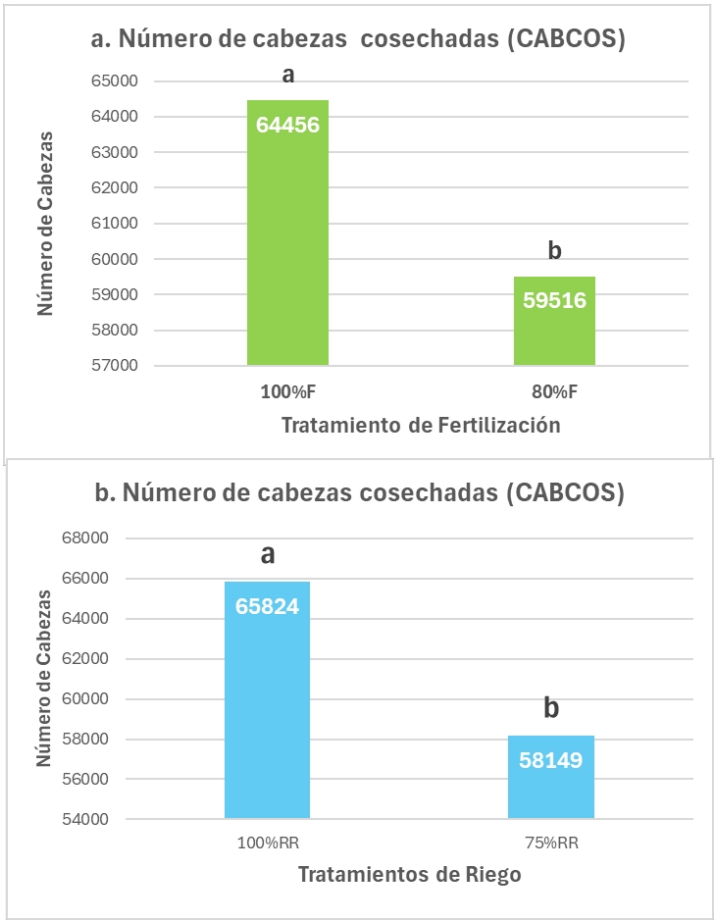


Figure 6. Trends in the number of heads harvested (CABCOS) for the main factors of fertilization and irrigation in lettuce cultivation. Pabellón Experimental Field. 2026.

Number of heads harvested (CABCOS). As mentioned earlier, this variable showed a significant difference ($p < 0.05$) in the main effect of fertilization. Figure 6a shows that the highest CABCOS values corresponded to the 100% fertilization treatment (64,456) compared to 59,516 for the 80% fertilization treatment; these values were statistically different according to Tukey's test of means ($p <$

0.05); whereas for the main effect of irrigation, the ANOVA detected significant differences ($p < 0.05$), Figure 6b shows that the highest CABCOS values corresponded to the irrigation treatment of 100% of the irrigation requirement (65,824) and the 75% irrigation treatment (58,149), which were statistically different according to Tukey's test of means ($p < 0.05$). Based on these results, the best strategy for maximizing CABCOS is to apply 100% of the crop's water requirements and combine this with the 100% fertilization treatment.

The analysis of variance showed a significant main effect of the fertilization factor on the CABCOS variable ($p < 0.05$). Reducing fertilization to 80% caused a drastic decrease in the value of the variable, decreasing by an average of 4,940 units compared to the optimal level of 100%. In contrast, the polymer factor did not show a direct influence on this response.

The analysis of variance revealed a significant main effect of the irrigation factor on the CABCOS variable ($p < 0.05$). Reducing irrigation to 75% caused a drastic decrease in the value of the variable, which fell by an average of 13,975 units compared to the optimal level of 100%. In contrast, the polymer factor did not have a direct influence on this response.

The marked sensitivity of the CABCOS variable to deficits in nutrient and water availability confirms that this parameter is closely linked to the immediate availability of these resources in the soil. The literature reports that a decrease in nutrient availability and a reduction in water potential restrict key physiological processes such as cell expansion or photosynthetic activity. The lack of response to the polymer in this scenario suggests that, for this particular variable, the physical properties of the soil or the plant's absorption rate are governed purely by the main input, limiting the polymer's regulatory effect.

Fresh weight yield (RDTO). For this variable, the main factors or effects—irrigation and fertilization—were also significant ($p < 0.05$); that is, the levels of these factors independently influenced lettuce productivity. Thus, for the irrigation levels shown in Figure 7a, the 100% irrigation treatment yielded 71.478 t/ha and the 75% treatment yielded 58.531 t/ha, which were statistically different according to Tukey's test of means ($p < 0.05$).

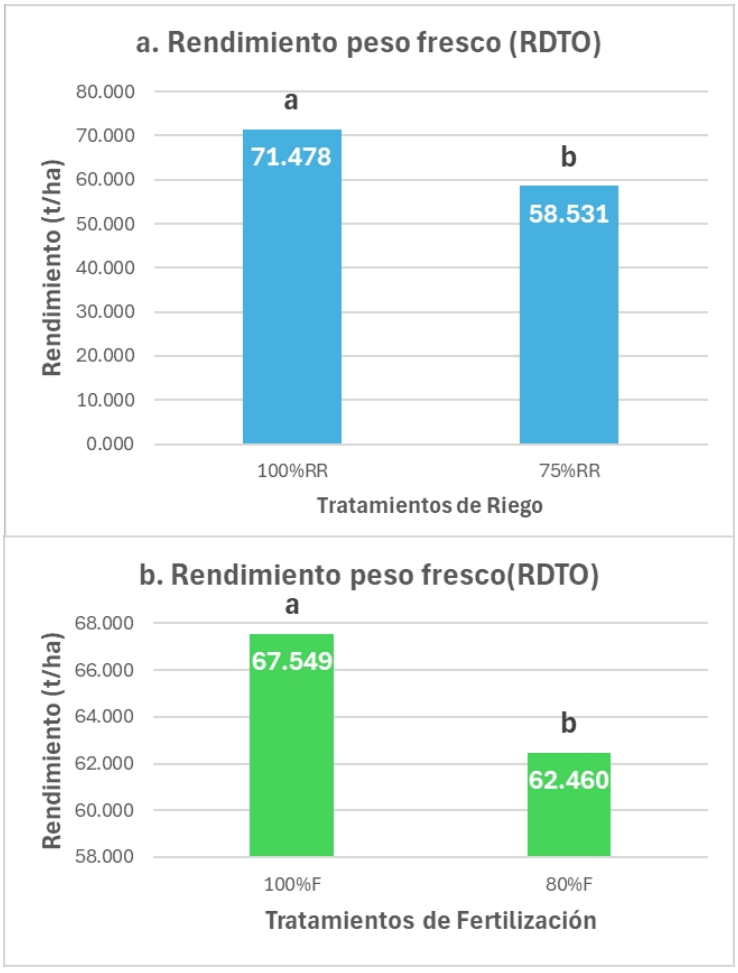


Figure 7. Lettuce yield behavior (fresh weight, RDTO) for the main factors of irrigation and fertilization in lettuce cultivation. Pabellón Experimental Field. 2026.

Meanwhile, for the fertilization factor in Figure 7b, it can be seen that the highest lettuce production corresponded to the 100% fertilization treatment with 67,549 t/ha, and the treatment with 80% fertilization yielded 62.460 t/ha, which were statistically different according to Tukey's test of means ($p < 0.05$).

To determine which main effect most strongly influences the fresh weight of lettuce at harvest (RDTO), a mixed linear model (Table a.6) was generated in the Appendix, showing that for the baseline treatment (100% Irrigation, 100% Fertilization, and 0 kg/ha Polymer), the yield was 79.58 t/ha; when irrigation was reduced to 75%, there was a decrease in yield of -14.38 t/ha (EE = 5.46 and $p = 0.01$), which was statistically significant, whereas reducing fertilization to 80% resulted in a decrease in yield of 5.14 t/ha (EE = 5.14 and $p = 0.163$), which was not significant. Based on these results, it is possible to reduce the level of fertilization but not the crop's water supply; to maximize the RDTO variable, it is necessary to meet 100% of the lettuce crop's water requirements and 100% of the fertilization treatment.

Efficient use of fertilizer (UEFN, UEFP, UEFK, UEFCa, UEFMg). As mentioned earlier, to estimate this variable, the percentage contribution of each element in the applied fertilization treatments was considered, multiplied by the fresh weight yield of lettuce (RDTO); Table 7 presents the average values of the index for each nutrient; since this is a yield-dependent variable, the results of the statistical analysis are similar to those of the original variable, in which highly significant differences ($P \geq 0.01$) were found for the fertilization factor and significant differences ($P \geq 0.05$) for the irrigation factor. The means of these indices were statistically different across both irrigation and fertilization levels, according to Tukey's test for means ($p < 0.05$).

Table 7. Test of means and their significance for efficient fertilizer use (UEFN, UEFP, UEFK, UEFCa, UEFMg) under the main effects of irrigation and fertilization in lettuce cultivation. Pabellón Experimental Field. 2026.

IRRIGATION FACTOR	EFFICIENT FERTILIZER USE (kg/kg)				
	UEFN	**UEFP**	**UEFK**	**UEFCa**	**UEFMg**
100%RR	23.43 to	14.39 a	35.98 a	4.18 a	2.51 a
75% RR	19.32 b	11.87 b	29.68 b	3.45 b	2.07 b
MSD	2.43	1.49	3.74	0.43	0.26
FERTILIZATION FACTOR	EFFICIENT FERTILIZER USE (kg/kg)				
	UEFN	**UEFP**	**UEFK**	**UEFCa**	**UEFMg**
100%F	24.58 to	15.10 a	37.74 a	4.39 a	2.63 a
80%F	18.18 b	11.17 b	27.92 b	3.25 b	1.95 b
MSD	1.33	0.81	3.46	0.24	0.14

*Entries with the same letter are statistically equivalent with a probability of P ≥ 0.05.

When analyzing the response to efficient nitrogen fertilizer use using a mixed linear model (Table A.8) in the Appendix, it was found that for the baseline treatment (100% irrigation + 100% Fertilizer + 0 kg/ha of Polymer), the index was 17.78 kilograms of green weight per kilogram of applied nitrogen (EE = 0.82 and p = 0.001); when fertilization was reduced to 80%, the index was -4.86 kg/kg (EE = 1.08 and p = 0.001), a highly significant difference; whereas when irrigation was reduced to 75%, the index was -3.21 kg/kg (EE = 1.12 and p = 0.006), a highly significant difference; whereas polymer doses, as a main effect, also affect the efficient use of nitrogen and the complementary fertilizers in the treatment; increasing the polymer dose to 18.08 kg/ha results in a value of -2.60 kg/kg (EE = 1.08 and p = 0.0206), and at 52.80 kg/ha, a change in this index of -2.22 kg/kg (EE = 1.08 and p = 0.0461), both of which are statistically significant.

It is important to note that when fertilization is reduced to 80% and irrigation is maintained at 100%, with 52.80 kg/ha of polymer, there is an increase in fertilizer use efficiency of 2.43 kg/kg (EE = 1.53 and p = 0.12); however, this response is not significant. The mixed models for the efficient use of

Phosphorus (UEFP), potassium (UEFK), calcium (UEFCa), and magnesium (UEFMg) are presented in Tables A.9 through A.12 of the Appendix.

Water Productivity (PAGUA). For this variable, a statistically significant difference was detected only for the main effect of fertilization. Figure 8 shows its behavior, where the 100% treatment yielded 22.234 kg of fresh weight of lettuce per cubic meter of water applied, and the 80% fertilization treatment yielded 20.448 kg of fresh weight of lettuce per cubic meter of water applied, which were statistically different according to Tukey's test ($p < 0.05$). This indicates that increasing fertilization by 20% also increases water use efficiency by 1.79 $^{kg/m^3}$.

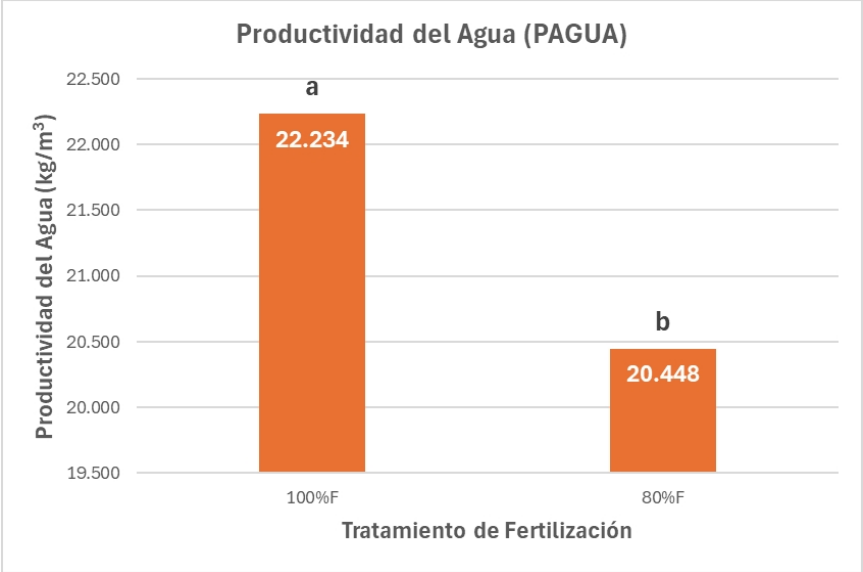


Figure 8. Water productivity (PAGUA) and the main effect of fertilization on lettuce cultivation. Pabellón Experimental Field. 2026.

Equatorial diameter (DE). This variable showed a significant effect of the fertilization treatment; Figure 9 shows its response to the evaluated levels, where the 100% treatment exhibited an equatorial diameter of
16.61 cm and the 80% fertilization treatment had a diameter of 15.76 cm. This difference was statistically significant according to Tukey's test for means ($p < 0.05$), suggesting that a 20% increase in fertilization

increases the equatorial diameter of the lettuce by 0.85 cm, which substantially improves product quality by increasing its size.

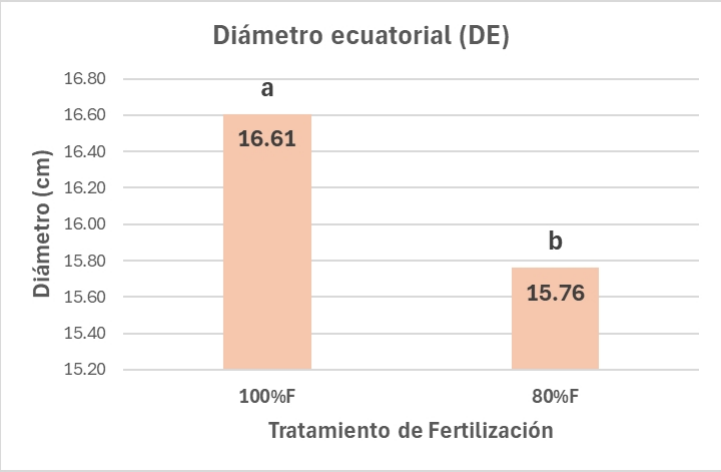


Figure 9. Equatorial diameter (ED), corresponding to the main effect of fertilization on lettuce cultivation. Pabellón Experimental Field. 2026.

Average weight per head (AWPH). This variable is considered part of lettuce quality and was affected by the main effect of fertilization. Figure 10 shows that the 100% treatment had the highest weight at
610.047 grams, and the 80% treatment at 522.816 grams, which were statistically different according to Tukey's test for mean differences ($P \geq 0.05$). This suggests that a 20% reduction in the fertilization treatment results in a decrease in average weight per head of approximately 87 grams.

DISCUSSION

A joint analysis of the water status and morphological development of lettuce (*Lactuca sativa* L.) reveals that the crop's response to reduced inputs is governed by distinct biological mechanisms involving water uptake and nutrient assimilation. On the one hand, the Relative Water Content (RWC) showed high sensitivity to complex third-order interactions; the combination of a water deficit at 75% of irrigation and

a reduction in fertilization to 80% under the low polymer dose of 18.08 kg/ha caused severe dehydration stress, reducing the RWC by 13.26%. However, this same polymer dose acted as an efficient water buffer when the fertilization level was maintained at an optimal level, increasing the RWC by 8.19%.

In contrast, Polar Diameter (PD) exhibited behavior independent of water availability, regulated primarily by nutrient availability and its interaction with higher polymer doses. Restricting fertilization to 80% alone significantly reduced the organ's longitudinal growth by 1.45 cm, an adverse effect that was completely mitigated and reversed by adding polymer at a rate of 52.80 kg/ha, resulting in a net increase of +0.60 cm compared to the control.

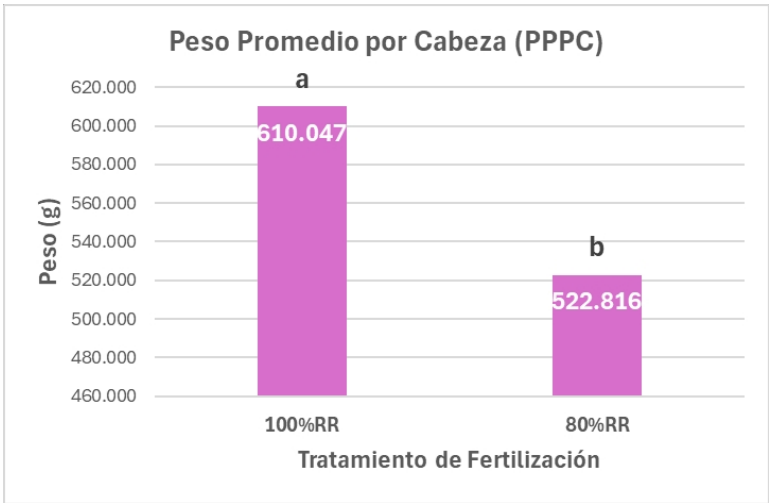


Figure 10. Average weight per head (PPPC), corresponding to the main effect of fertilization on lettuce cultivation. Pabellón Experimental Field. 2026.

From a physiological perspective, these results suggest that low polymer doses (18.08 kg/ha) effectively optimize soil water potential in the root zone under moderate drought conditions, but are insufficient to maintain cellular turgor if the plant's osmotic pressure is compromised due to a simultaneous nutrient deficit. In contrast, high doses (52.08 kg/ha) appear to enhance cation exchange capacity and nutrient retention in the rhizosphere, compensating for fertilizer deficiency and stimulating cell elongation in the tissue.

In conclusion, to optimize sustainable lettuce production, the use of low polymer doses is not recommended when both inputs are reduced simultaneously; a decoupled strategy is recommended: use 18.08 kg/ha of polymer if the goal is exclusively water savings (25%), or scale up to 52.80 kg/ha if the objective is high-efficiency management that tolerates combined reductions in water and fertilizer without compromising the crop's commercial quality.

The absence of statistically significant effects of polymer doses on the percentage of dry matter at harvest in lettuce (*Lactuca sativa* L.) suggests that the dynamics of biomass accumulation and the plant's internal water balance were not significantly altered by this amendment under the evaluated conditions. Physiologically, dry matter in leafy vegetables represents the net balance between the crop's photosynthetic rate and respiratory costs. Although superabsorbent polymers favorably modify the soil's hydrophysical properties by increasing water-holding capacity and modulating water release, their impact is typically more evident under severe water-stress conditions or in soils with markedly sandy textures.

In the present study, the baseline water supply corresponding to a 75% irrigation depth may have been sufficient to meet the water demands of lettuce, maintaining soil water potential within optimal ranges for root uptake. Under this sufficiency scenario, the additional water provided by the polymer doses (18.08, 36.08, and 52.80 kg/ha) did not result in greater water use efficiency or

an increase in the photosynthetic rate that would alter the percentage of structural assimilates.

These findings are consistent with those reported by various authors, who note that the application of polymers tends to increase fresh weight or plant diameter due to greater cellular turgor, but rarely alters the proportion or percentage of dry matter if baseline moisture and fertilization levels already meet the crop's physiological requirements. Therefore, under agricultural management practices with a stable water supply and optimal nutrition, the incorporation of polymers does not represent a limiting factor or an additional stimulus for dry matter accumulation in the lettuce crop.

CONCLUSIONS

Under the conditions of this study, the following conclusions are drawn:

1. Polymer dose of 0.00 kg/ha: Maintains an acceptable CRA (76.66%) and good stem diameter only if 100% of the fertilizer is applied. When fertilizer is reduced to 80%, the plant diameter decreases by 1.45 cm. It offers no protection against unforeseen events.

2. Dose of 18.08 kg/ha: This is the riskiest option. If, for any reason, the crop experiences dual stress (irrigation reduced to 75% and fertilization to 80%), this dose causes a critical drop of -13.26% in the CRA; from an agronomic perspective, it fails to achieve the desired water retention effect and destabilizes the plant.

3. Dose of 36.08 kg/ha: This stabilizes the plant's water status (preventing the drop in CRA observed at the low dose). Furthermore, when fertilizer is reduced to 80%, this rate almost completely reverses the damage, recovering +1.425 cm in polar diameter; this option from the scientific recommendation is geared toward efficiency and resource optimization.

4. Dose of 52.80 kg/ha: This dose offers the highest product quality. It prevents water stress in the CRA and, in the face of a fertilizer deficit (80%), not only compensates for the loss in diameter but significantly exceeds it, contributing an additional +2.05 cm.

5. Based on these results, it is important to conduct a validation phase on fields managed by commercial growers, incorporating high polymer doses, while keeping irrigation and fertilization factors constant. At harvest, quantitative and qualitative variables—including nutraceutical properties, palatability, and lettuce shelf life—should be assessed.

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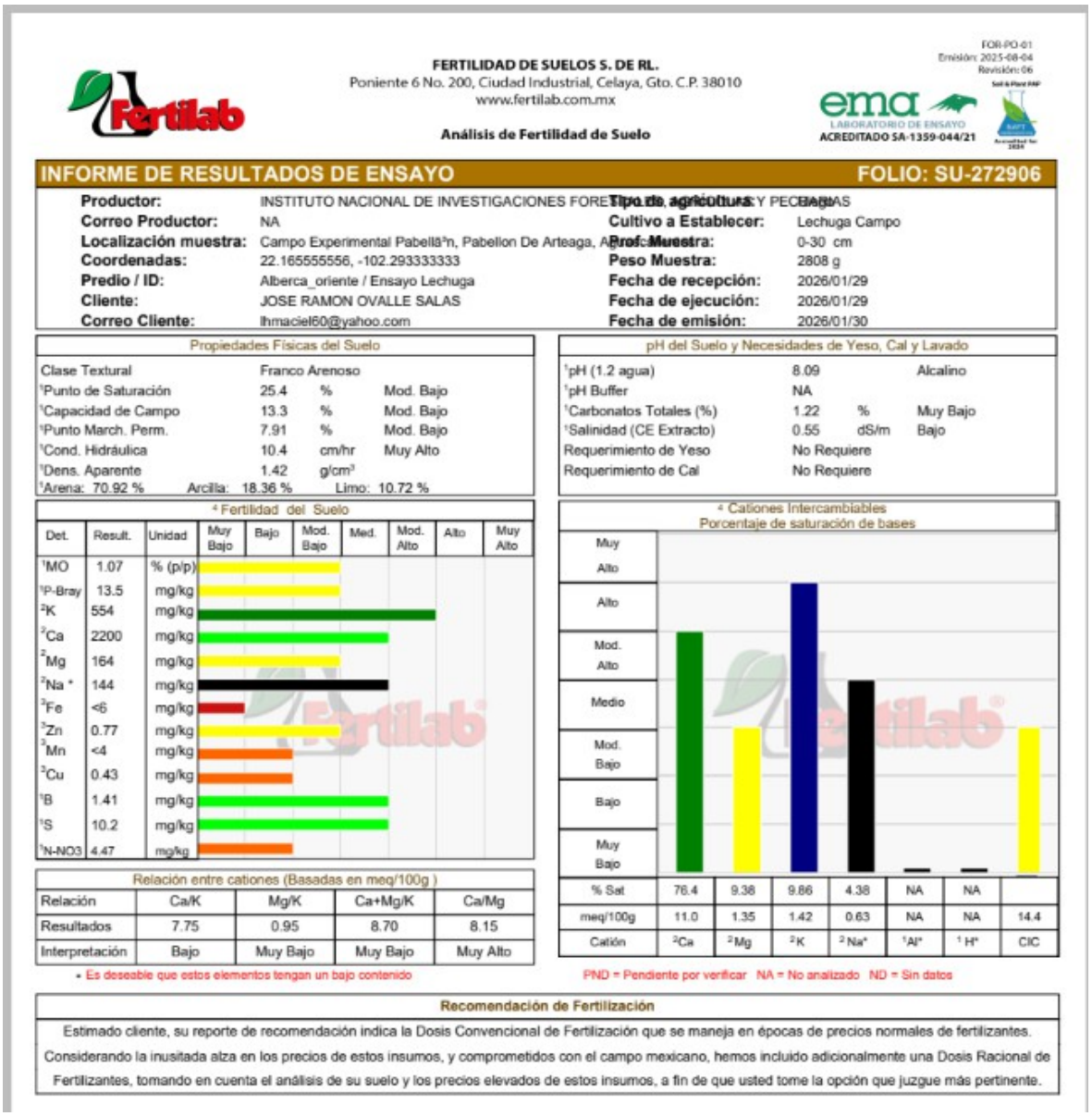
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APPENDIX



FERTILIDAD DE SUELOS S. DE RL.
Poniente 6 No. 200, Ciudad Industrial, Celaya, Gto. C.P. 38010
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Análisis de Fertilidad de Suelo

FOR-PO-01
Emisión: 2025-08-04
Revisión: 06

ema LABORATORIO DE ENSAYO
ACREDITADO SA-1359-044/21

INFORME DE RESULTADOS DE ENSAYO — **FOLIO: SU-272906**

Productor:	INSTITUTO NACIONAL DE INVESTIGACIONES FORE[illegible]Y PECUARIAS	**Tipo de agricultura:**	[illegible]
Correo Productor:	NA	**Cultivo a Establecer:**	Lechuga Campo
Localización muestra:	Campo Experimental Pabellã³n, Pabellon De Arteaga, A[illegible]	**Prof. Muestra:**	0-30 cm
Coordenadas:	22.165555556, -102.293333333	**Peso Muestra:**	2808 g
Predio / ID:	Alberca_oriente / Ensayo Lechuga	**Fecha de recepción:**	2026/01/29
Cliente:	JOSE RAMON OVALLE SALAS	**Fecha de ejecución:**	2026/01/29
Correo Cliente:	lhmaciel60@yahoo.com	**Fecha de emisión:**	2026/01/30

Propiedades Físicas del Suelo

Clase Textural	Franco Arenoso		
[1]Punto de Saturación	25.4	%	Mod. Bajo
[1]Capacidad de Campo	13.3	%	Mod. Bajo
[1]Punto March. Perm.	7.91	%	Mod. Bajo
[1]Cond. Hidráulica	10.4	cm/hr	Muy Alto
[1]Dens. Aparente	1.42	g/cm³	

[1]Arena: 70.92 % Arcilla: 18.36 % Limo: 10.72 %

pH del Suelo y Necesidades de Yeso, Cal y Lavado

[1]pH (1.2 agua)	8.09		Alcalino
[1]pH Buffer	NA		
[1]Carbonatos Totales (%)	1.22	%	Muy Bajo
[1]Salinidad (CE Extracto)	0.55	dS/m	Bajo
Requerimiento de Yeso	No Requiere		
Requerimiento de Cal	No Requiere		

[4] Fertilidad del Suelo

Det.	Result.	Unidad	Muy Bajo	Bajo	Mod. Bajo	Med.	Mod. Alto	Alto	Muy Alto
[1]MO	1.07	% (p/p)							
[1]P-Bray	13.5	mg/kg							
[2]K	554	mg/kg							
[2]Ca	2200	mg/kg							
[2]Mg	164	mg/kg							
[2]Na *	144	mg/kg							
[3]Fe	<6	mg/kg							
[3]Zn	0.77	mg/kg							
[3]Mn	<4	mg/kg							
[3]Cu	0.43	mg/kg							
[1]B	1.41	mg/kg							
[1]S	10.2	mg/kg							
[1]N-NO3	4.47	mg/kg							

[4] Cationes Intercambiables
Porcentaje de saturación de bases

% Sat	76.4	9.38	9.86	4.38	NA	NA	
meq/100g	11.0	1.35	1.42	0.63	NA	NA	14.4
Catión	[2]Ca	[2]Mg	[2]K	[2]Na*	[1]Al*	[1]H*	CIC

Relación entre cationes (Basadas en meq/100g)

Relación	Ca/K	Mg/K	Ca+Mg/K	Ca/Mg
Resultados	7.75	0.95	8.70	8.15
Interpretación	Bajo	Muy Bajo	Muy Bajo	Muy Alto

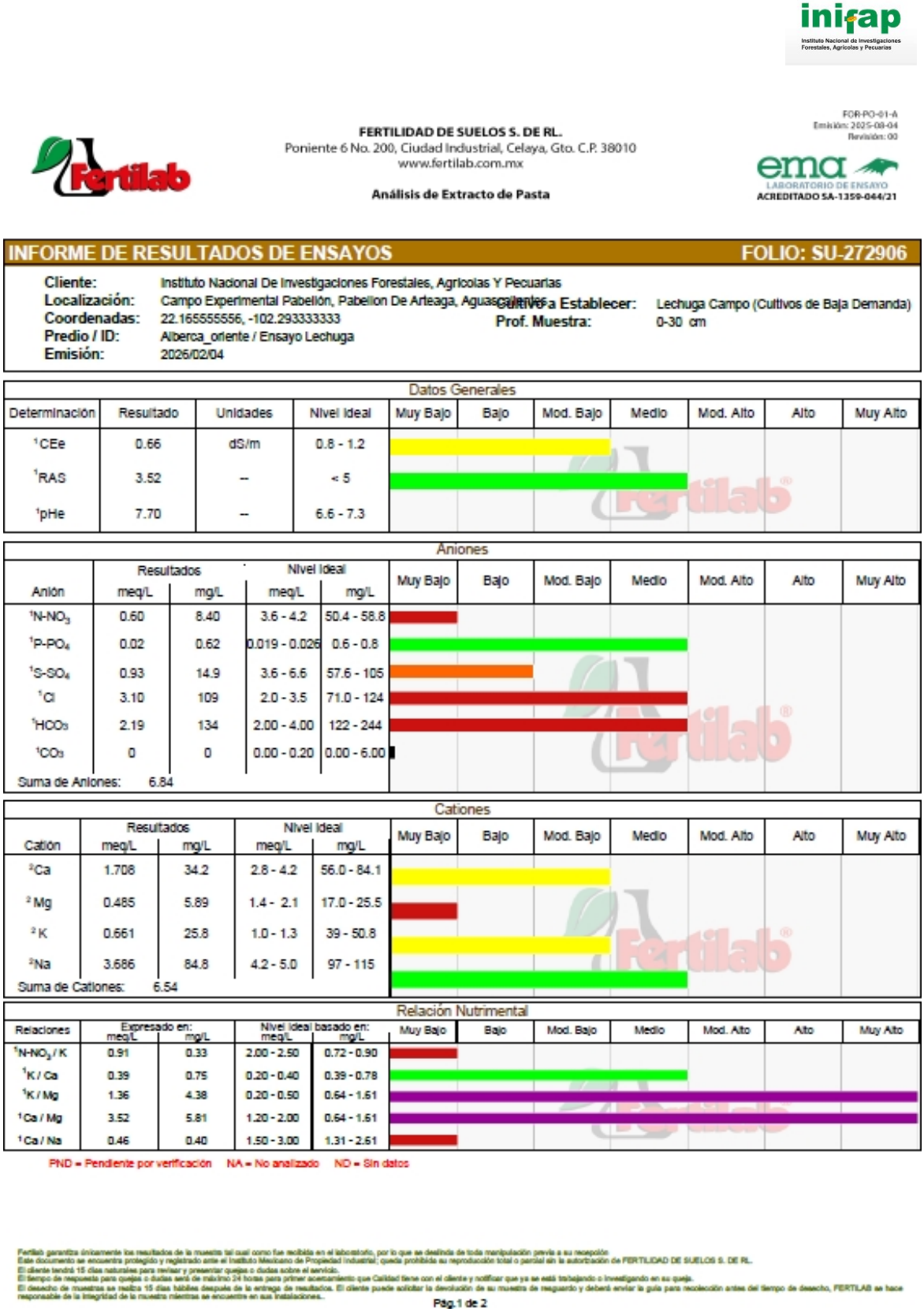
* Es deseable que estos elementos tengan un bajo contenido

PND = Pendiente por verificar NA = No analizado ND = Sin datos

Recomendación de Fertilización

Estimado cliente, su reporte de recomendación indica la Dosis Convencional de Fertilización que se maneja en épocas de precios normales de fertilizantes. Considerando la inusitada alza en los precios de estos insumos, y comprometidos con el campo mexicano, hemos incluido adicionalmente una Dosis Racional de Fertilizantes, tomando en cuenta el análisis de su suelo y los precios elevados de estos insumos, a fin de que usted tome la opción que juzgue más pertinente.

Figure a.1. Soil fertility analysis of the site where the polymer evaluation was conducted. Pabellón Experimental Field. 2026.



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Análisis de Extracto de Pasta

FOR-PO-01-A
Emisión: 2025-08-04
Revisión: 00

ACREDITADO SA-1359-044/21

INFORME DE RESULTADOS DE ENSAYOS — FOLIO: SU-272906

Cliente: Instituto Nacional De Investigaciones Forestales, Agricolas Y Pecuarias
Localización: Campo Experimental Pabellón, Pabellon De Arteaga, Aguascalientes
Coordenadas: 22.165555556, -102.293333333
Predio / ID: Alberca_oriente / Ensayo Lechuga
Emisión: 2026/02/04
Cultivo a Establecer: Lechuga Campo (Cultivos de Baja Demanda)
Prof. Muestra: 0-30 cm

Datos Generales

Determinación	Resultado	Unidades	Nivel Ideal
[1]CEe	0.66	dS/m	0.8 - 1.2
[1]RAS	3.52	--	< 5
[1]pHe	7.70	--	6.6 - 7.3

Aniones

Anión	Resultados meq/L	Resultados mg/L	Nivel Ideal meq/L	Nivel Ideal mg/L
[1]N-NO_3	0.60	8.40	3.6 - 4.2	50.4 - 58.8
[1]P-PO_4	0.02	0.62	0.019 - 0.026	0.6 - 0.8
[1]S-SO_4	0.93	14.9	3.6 - 6.6	57.6 - 105
[1]Cl	3.10	109	2.0 - 3.5	71.0 - 124
[1]HCO_3	2.19	134	2.00 - 4.00	122 - 244
[1]CO_3	0	0	0.00 - 0.20	0.00 - 6.00
Suma de Aniones:	6.84			

Cationes

Catión	Resultados meq/L	Resultados mg/L	Nivel Ideal meq/L	Nivel Ideal mg/L
[2]Ca	1.708	34.2	2.8 - 4.2	56.0 - 84.1
[2]Mg	0.485	5.89	1.4 - 2.1	17.0 - 25.5
[2]K	0.661	25.8	1.0 - 1.3	39 - 50.8
[2]Na	3.686	84.8	4.2 - 5.0	97 - 115
Suma de Cationes:	6.54			

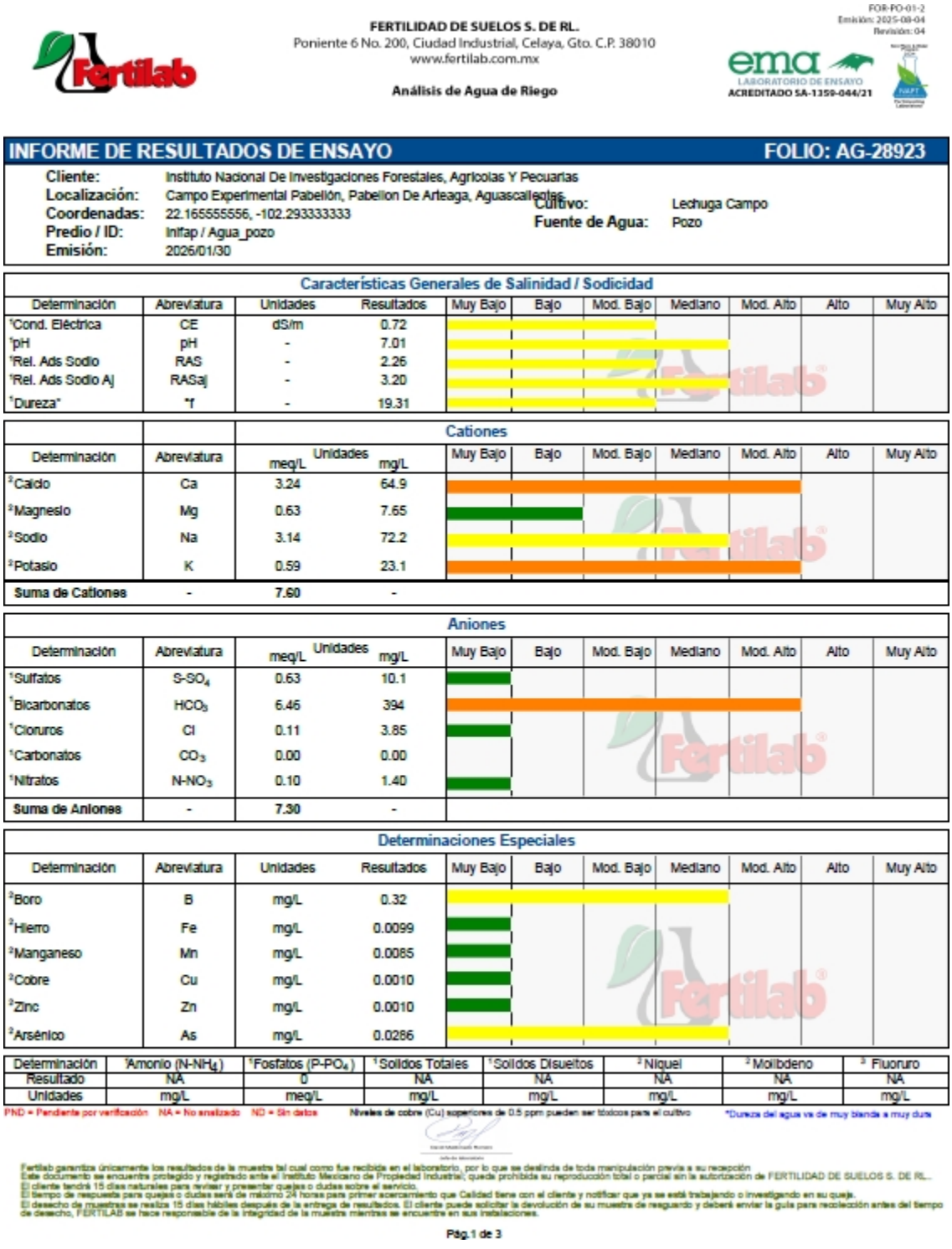
Relación Nutrimental

Relaciones	Expresado en: meq/L	Expresado en: mg/L	Nivel Ideal basado en: meq/L	Nivel Ideal basado en: mg/L
[1]N-NO_3 / K	0.91	0.33	2.00 - 2.50	0.72 - 0.90
[1]K / Ca	0.39	0.75	0.20 - 0.40	0.39 - 0.78
[1]K / Mg	1.36	4.38	0.20 - 0.50	0.64 - 1.61
[1]Ca / Mg	3.52	5.81	1.20 - 2.00	0.64 - 1.61
[1]Ca / Na	0.46	0.40	1.50 - 3.00	1.31 - 2.61

PND = Pendiente por verificación NA = No analizado ND = Sin datos

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Figure a.2. Soil salinity analysis (paste extract) from the site where the polymer evaluation was conducted. Pabellón Experimental Field. 2026.



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Análisis de Agua de Riego

FOR-PO-01-2
Emisión: 2025-08-04
Revisión: 04

ema LABORATORIO DE ENSAYO ACREDITADO SA-1359-044/21

INFORME DE RESULTADOS DE ENSAYO **FOLIO: AG-28923**

Cliente:	Instituto Nacional De Investigaciones Forestales, Agricolas Y Pecuarias		
Localización:	Campo Experimental Pabellón, Pabellon De Arteaga, Aguascalientes	**Cultivo:**	Lechuga Campo
Coordenadas:	22.165555556, -102.293333333	**Fuente de Agua:**	Pozo
Predio / ID:	Inifap / Agua_pozo		
Emisión:	2026/01/30		

Características Generales de Salinidad / Sodicidad

Determinación	Abreviatura	Unidades	Resultados	Muy Bajo	Bajo	Mod. Bajo	Mediano	Mod. Alto	Alto	Muy Alto
[1]Cond. Eléctrica	CE	dS/m	0.72							
[1]pH	pH	-	7.01							
[1]Rel. Ads Sodio	RAS	-	2.26							
[1]Rel. Ads Sodio Aj	RASaj	-	3.20							
[1]Dureza*	*f	-	19.31							

Cationes

Determinación	Abreviatura	Unidades meq/L	Unidades mg/L	Muy Bajo	Bajo	Mod. Bajo	Mediano	Mod. Alto	Alto	Muy Alto
[2]Calcio	Ca	3.24	64.9							
[2]Magnesio	Mg	0.63	7.65							
[2]Sodio	Na	3.14	72.2							
[2]Potasio	K	0.59	23.1							
Suma de Cationes	-	**7.60**	-							

Aniones

Determinación	Abreviatura	Unidades meq/L	Unidades mg/L	Muy Bajo	Bajo	Mod. Bajo	Mediano	Mod. Alto	Alto	Muy Alto
[1]Sulfatos	$S\text{-}SO_4$	0.63	10.1							
[1]Bicarbonatos	HCO_3	6.46	394							
[1]Cloruros	Cl	0.11	3.85							
[1]Carbonatos	CO_3	0.00	0.00							
[1]Nitratos	$N\text{-}NO_3$	0.10	1.40							
Suma de Aniones	-	**7.30**	-							

Determinaciones Especiales

Determinación	Abreviatura	Unidades	Resultados	Muy Bajo	Bajo	Mod. Bajo	Mediano	Mod. Alto	Alto	Muy Alto
[2]Boro	B	mg/L	0.32							
[2]Hierro	Fe	mg/L	0.0099							
[2]Manganeso	Mn	mg/L	0.0085							
[2]Cobre	Cu	mg/L	0.0010							
[2]Zinc	Zn	mg/L	0.0010							
[2]Arsénico	As	mg/L	0.0286							

Determinación	[1]Amonio ($N\text{-}NH_4$)	[1]Fosfatos ($P\text{-}PO_4$)	[1]Solidos Totales	[1]Solidos Disueltos	[2]Niquel	[2]Molibdeno	[3] Fluoruro
Resultado	NA	0	NA	NA	NA	NA	NA
Unidades	mg/L	meq/L	mg/L	mg/L	mg/L	mg/L	mg/L

PND = Pendiente por verificación NA = No analizado ND = Sin datos Niveles de cobre (Cu) superiores de 0.5 ppm pueden ser tóxicos para el cultivo *Dureza del agua va de muy blanda a muy dura

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El cliente tendrá 15 días naturales para revisar y presentar quejas o dudas sobre el servicio.
El tiempo de respuesta para quejas o dudas será de máximo 24 horas para primer acercamiento que Calidad tiene con el cliente y notificar que ya se está trabajando o investigando en su queja.
El desecho de muestras se realiza 15 días hábiles después de la entrega de resultados. El cliente puede solicitar la devolución de su muestra de resguardo y deberá enviar la guía para recolección antes del tiempo de desecho, FERTILAB se hace responsable de la integridad de la muestra mientras se encuentre en sus instalaciones.

Figure a.3. Irrigation water quality analysis of the water source where the polymer evaluation was conducted. Pabellón Experimental Field. 2026.

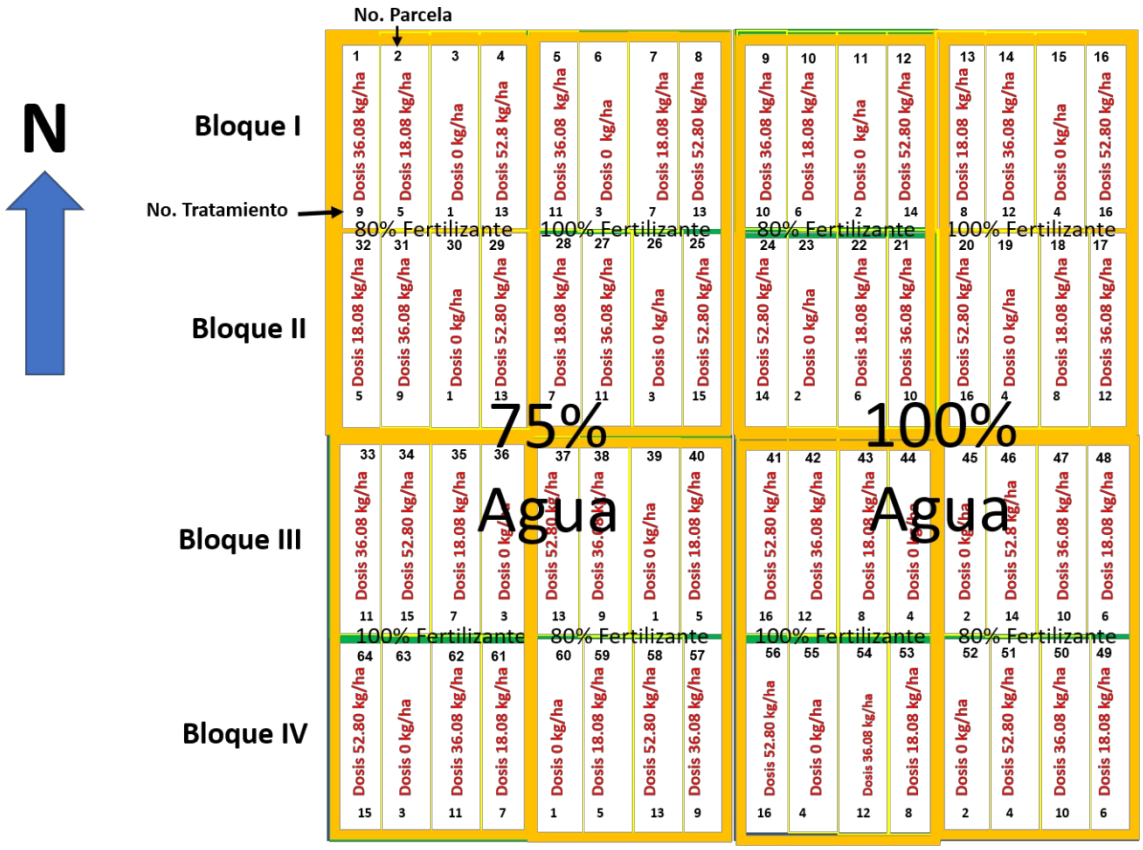


Figure a.4. Distribution of treatments and replicates in the lettuce experimental trial field. Pabellón Experimental Field. 2026.

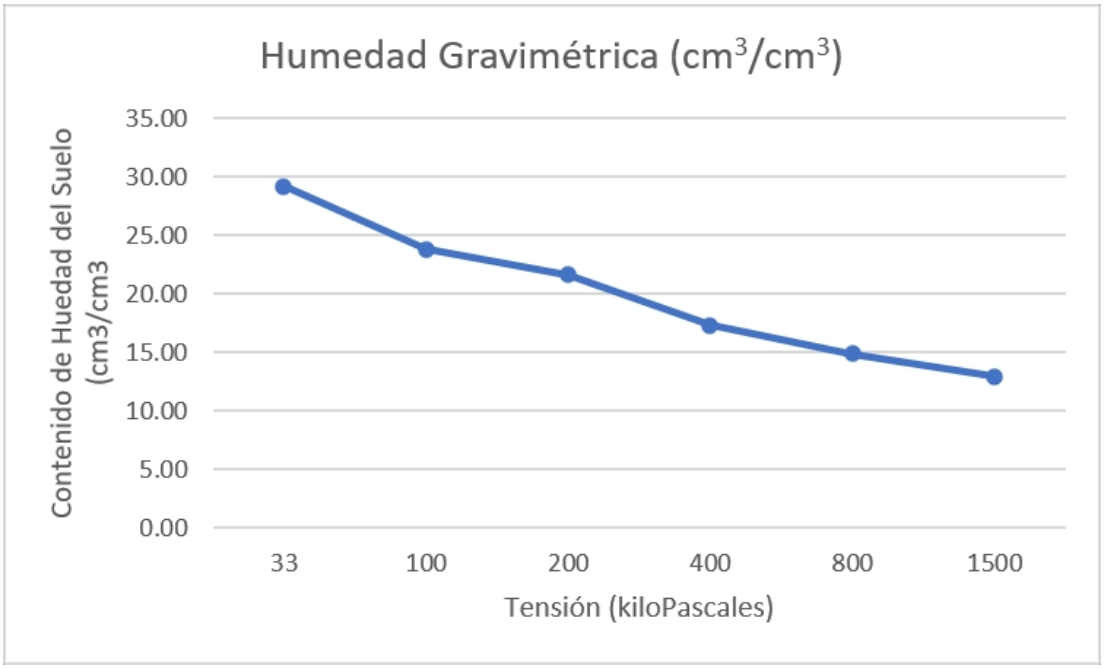


Figure a.5. Soil moisture retention curve for the field where the lettuce experiment was established. Pabellón Experimental Field. 2026.

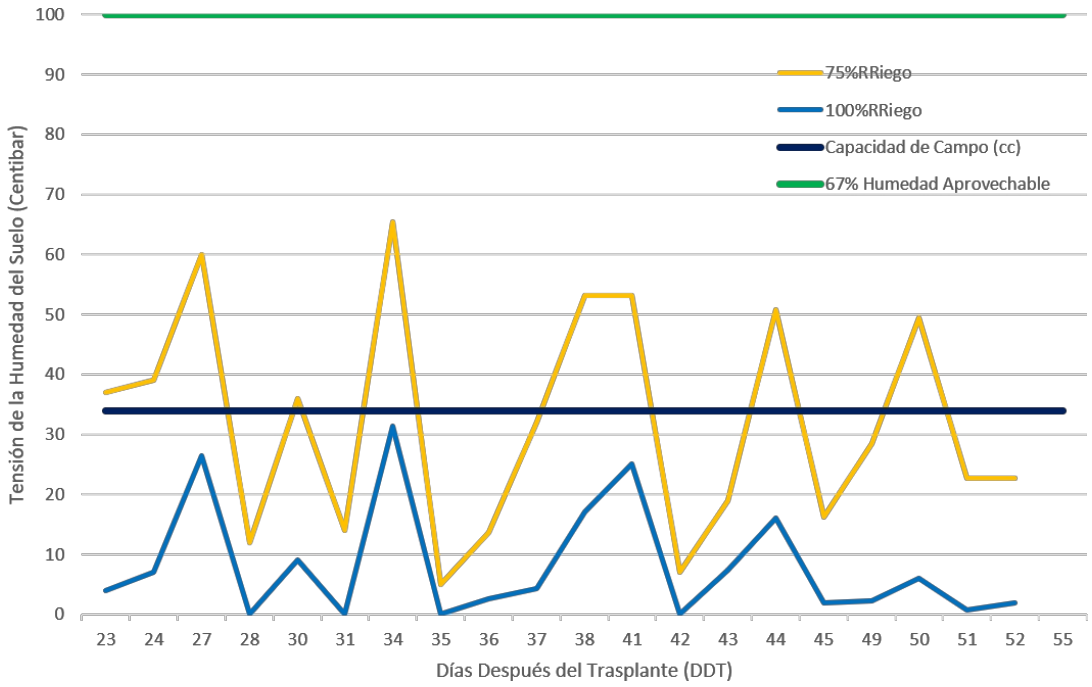


Figure a.6. Soil moisture dynamics expressed in centibarios (Cb) in the experimental lettuce trial. Pabellón Experimental Field. 2026.

Table A.1. Estimates of fixed effects and variance components for the effects Random effects of the mixed linear model for developing lettuce plant height (APDES) expressed in cm. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 75%, Fertilizer 80%, Pol 0]	9.9	0.4874	24.98	20.311	<2e-16 ***
100% Irrigation	-0.025	0.6131	33.82	-0.041	0.968
100% Fertilization	0.4	0.5825	42	0.687	0.496
Polymer 18.08	-0.6	0.5825	42	-1.03	0.309
Polymer 36.08	-0.8	0.5825	42	-1.373	0.177
Polymer 52.80	-0.8	0.5825	42	-1.373	0.177
Irrigation 100%:Fertilizer 100%	0.575	0.8238	42	0.698	0.489
Irrigation 100%: Polymer 18.08	1.05	0.8238	42	1.275	0.209
Irrigation 100%: Polymer 36.08	1.175	0.8238	42	1.426	0.161
Irrigation 100%: Polymer 52.80	0.35	0.8238	42	0.425	0.673
Fert 100%: Polymer 18.08	-1.667E-15	0.8238	42	0	1
Fert 100%: Polymer 36.08	0.275	0.8238	42	0.334	0.74
Fert 100%: Polymer 52.80	-1.125	0.8238	42	-1.366	0.179
Irrigation 100%: Fertilizer 100%: Polymer 18.08	-1.75	1.165	42	-1.502	0.141
Irrigation 100%: Fertilizer 100%: Polymer 36.08	-1,825	1.165	42	-1.567	0.125
Irrigation 100%: Fertilizer 100%: Polymer 52.80	1.225	1.165	42	1.051	0.299
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.19859	0.4456			
Main Plot (rep:irrigation)	0.07309	0.2703			
Residual (Error)	0.67863	0.8238			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main

Table A.2. Estimates of fixed effects and variance components for the effects random effects of the mixed linear model for relative water content (RWC) expressed as a percentage. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	76.662	1.863	45.42	41.145	< 0.001 ***
75% Irrigation	-1,555	2.635	45.416	-0.59	0.5581
Fertilization 80%	1,263	2,556	35.08	0.494	0.6242
Polymer 18.08	-0.815	2.472	35.998	-0.33	0.7436
Polymer 36.08	3.01	2.472	35.998	1.218	0.2313
Polymer 52.80	2,772	2,472	35,998	1,121	0.2695
Irrigation 75%: Fertilizer 80%	3.269	3.615	35.08	0.904	0.372
Irrigation 75%: Polymer 18.08	8.198	3.496	35.998	2.345	0.0247 *
Irrigation 75%: Polymer 36.08	-1,191	3,496	35,998	-0.341	0.7353
Irrigation 75%: Polymer 52.80	-0.301	3.496	35.998	-0.086	0.9319
Fert 80%: Polymer 18.08	1.38	3.496	35.998	0.395	0.6953
Fert 80%: Polymer 36.08	-2,506	3,496	35.998	-0.717	0.4782
Fert 80%: Polymer 52.80	-3.103	3.496	35.998	-0.887	0.3807
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-13,265	4.945	35.998	-2.683	0.011 *
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-5,072	4,945	35.998	-1.026	0.3119
Irrigation 75%: Fertilizer 80%: Polymer 52.80	1,326	4,945	35.998	0.268	0.7901
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	3.127E-09	0.00005592			
Main Plot (rep:irrigation)	0.8203	0.9057			
Residual (Error)	12.22	3.496			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.3. Estimates of fixed effects and variance components for the effects random effects of the mixed linear model for polar diameter (DP) expressed in cm. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	13.55	0.4173	27.8705	32.467	< 2e-16
Irrigation 75%	-0.2	0.563	21.0365	-0.355	0.72593
Fertilization 80%	-1.45	0.4915	42	-2.95	0.00518 **
Polymer 18.08	-0.575	0.4915	42	-1.17	0.24869
Polymer 36.08	-0.6	0.4915	42	-1.221	0.22904
Polymer 52.80	-0.575	0.4915	42	-1.17	0.24869
Irrigation 75%: Fertilizer 80%	0.275	0.6952	42	0.396	0.69441
Irrigation 75%: Polymer 18.08	-0.5	0.6952	42	-0.719	0.47597
Irrigation 75%: Polymer 36.08	-0.05	0.6952	42	-0.072	0.943
Irrigation 75%: Polymer 52.80	-0.4	0.6952	42	-0.575	0.56809
Fert 80%: Polymer 18.08	1.325	0.6952	42	1.906	0.06351 .
Fert 80%: Polymer 36.08	1.425	0.6952	42	2.05	0.04665 *
Fert 80%: Polymer 52.80	2.05	0.6952	42	2.949	0.00519 **
Irrigation 75%:Fertilizer 80%:Polymer 18.08	0.175	0.9831	42	0.178	0.85957
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-0.55	0.9831	42	-0.559	0.57883
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-1.5	0.9831	42	-1.526	0.13456
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.06286	0.2507			
Main Plot (rep:irrigation)	0.1506	0.3881			
Residual (Error)	0.48325	0.6952			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.4. Estimates of fixed effects and variance components for the effects in the mixed linear model for percentage of dry matter at harvest (PMSC) expressed as a percentage. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	3.1155	0.2109	37.2915	14.774	<2e-16 ***
Irrigation 75%	0.283	0.2982	37.2915	0.949	0.3487
Fertilization 80%	0.4585	0.2663	42.0002	1.722	0.0925 .
Polymer 18.08	0.3505	0.2663	42.0002	1.316	0.1953
Polymer 36.08	0.1868	0.2663	42.0002	0.701	0.487
Polymer 52.80	0.4287	0.2663	42.0002	1.61	0.1149
Irrigation 75%: Fertilizer 80%	0.2575	0.3766	42.0002	0.684	0.4979
Irrigation 75%: Polymer 18.08	-0.3567	0.3766	42.0002	-0.947	0.3489
Irrigation 75%: Polymer 36.08	0.2737	0.3766	42.0002	0.727	0.4714
Irrigation 75%: Polymer 52.80	-0.3767	0.3766	42.0002	-1	0.3229
Fert 80%: Polymer 18.08	-0.4015	0.3766	42.0002	-1.066	0.2925
Fert 80%: Polymer 36.08	-0.506	0.3766	42.0002	-1.344	0.1863
Fert 80%: Polymer 52.80	-0.4735	0.3766	42.0002	-1.257	0.2156
Irrigation 75%: Fertilizer 80%: Polymer 18.08	0.3125	0.5326	42.0002	0.587	0.5605
Irrigation 75%:Fertilizer 80%:Polymer 36.08	0.1715	0.5326	42.0002	0.322	0.7491
Irrigation 75%:Fertilizer 80%:Polymer 52.80	0.5875	0.5326	42.0002	1.103	0.2763
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0	0			
Main Plot (rep:irrigation)	0.03602	0.1898			
Residual (Error)	0.14185	0.3766			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.5. Estimates of fixed effects and variance components for the effects in the mixed linear model for harvest water content (HWC) expressed as a percentage. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 75%, Fertilizer 80%, Pol 0]	95.8855	0.21087	37.29147	454.706	<2e-16 ***
100% Irrigation	0.5405	0.29822	37.29147	1.812	0.078 .
100% Fertilization	0.716	0.26631	42.00017	2.689	0.0102 *
Polymer 18.08	0.09525	0.26631	42.00017	0.358	0.7224
Polymer 36.08	-0.126	0.26631	42.00017	-0.473	0.6386
Polymer 52.80	-0.166	0.26631	42.00017	-0.623	0.5364
Irrigation 100%:Fertilizer 100%	-0.2575	0.37663	42.00017	-0.684	0.4979
Irrigation 100%: Polymer 18.08	-0.04425	0.37663	42.00017	-0.117	0.907
Irrigation 100%: Polymer 36.08	0.44525	0.37663	42.00017	1.182	0.2438
Irrigation 100%: Polymer 52.80	0.21075	0.37663	42.00017	0.56	0.5787
Fert 100%: Polymer 18.08	-0.089	0.37663	42.00017	-0.236	0.8143
Fert 100%: Polymer 36.08	-0.3345	0.37663	42.00017	-0.888	0.3795
Fert 100%: Polymer 52.80	0.114	0.37663	42.00017	0.303	0.7636
Irrigation 100%: Fertilizer 100%: Polymer 18.08	-0.3125	0.53263	42.00017	-0.587	0.5605
Irrigation 100%: Fertilizer 100%: Polymer 36.08	-0.1715	0.53263	42.00017	-0.322	0.7491
Irrigation 100%:Fertilizer 100%:Polymer 52.80	-0.5875	0.53263	42.00017	-1.103	0.2763
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0	0			
Main Plot (rep:irrigation)	0.03602	0.1898			
Residual (Error)	0.14185	0.3766			

Table footnote: Significance codes: 0 ***" 0.001*** *" 0.01* " 0.05. rep:irrigation represents the error term for the main plot

Table A.6. Estimates of fixed effects and variance components for the effects random effects of the mixed linear model for fresh weight at harvest (RDTO) expressed in t/ha. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	79.576	3,941	41.02	20,191	<2e-16 ***
Irrigation 75%	-14,383	5,457	32,221	-2,636	0.0128 *
Fertilization 80%	-7,296	5.14	42,002	-1,419	0.1632
Polymer 18.08	-11,678	5.14	42.002	-2.272	0.0283 *
Polymer 36.08	-7.854	5.14	42.002	-1.528	0.134
Polymer 52.80	-9,976	5.14	42.002	-1,941	0.059
Irrigation 75%: Fertilizer 80%	-2,717	7.27	42.002	-0.374	0.7105
Irrigation 75%: Polymer 18.08	8.363	7.27	42.002	1.15	0.2565
Irrigation 75%: Polymer 36.08	3.278	7.27	42.002	0.451	0.6544
Irrigation 75%: Polymer 52.80	8.695	7.27	42.002	1.196	0.2384
Fert 80%: Polymer 18.08	4.673	7.27	42,002	0.643	0.5238
Fert 80%: Polymer 36.08	7.632	7.27	42.002	1.05	0.2998
Fert 80%: Polymer 52.80	11.111	7.27	42.002	1.528	0.1339
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-1.889	10,281	42,002	-0.184	0.8551
Irrigation 75%: Fertilizer 80%: Polymer 36.08	-1,096	10.281	42.002	-0.107	0.9156
Irrigation 75%: Fertilizer 80%: Polymer 52.80	-15,328	10.281	42,002	-1,491	0.1434
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	2.574	1.604364			
Main Plot (rep:irrigation)	6.712	2.590788			
Residual (Error)	52.85	7.269556			

Table footnote: Significance codes: 0 ***" 0.001*** *" 0.01* " 0.05. rep:irrigation represents the error term for the main plot

Table A.7. Estimates of fixed effects and variance components for the effects random effects in the mixed linear model for water productivity (PAGUA), expressed in kg/m^3. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Weeding 0]	24.1295	1.3264	38.0602	18.191	<2e-16 ***
Irrigation 75%	-0.7315	1.838	28.0763	-0.398	0.6937
Fertilization 80%	-2,212	1.6899	42	-1.309	0.1977
Polymer 18.08	-3.5412	1.6899	42	-2.095	0.0422 *
Polymer 36.08	-2.3813	1.6899	42	-1.409	0.1662
Polymer 52.80	-3.0248	1.6899	42	-1.79	0.0807
Irrigation 75%: Fertilizer 80%	-1.3818	2.3899	42	-0.578	0.5662
Irrigation 75%: Polymer 18.08	2.3518	2.3899	42	0.984	0.3307
Irrigation 75%: Polymer 36.08	0.7392	2.3899	42	0.309	0.7586
Irrigation 75%: Polymer 52.80	2.5648	2.3899	42	1.073	0.2893
Fert 80%: Polymer 18.08	1.4172	2.3899	42	0.593	0.5564
Fert 80%: Polymer 36.08	2.3138	2.3899	42	0.968	0.3385
Fert 80%: Polymer 52.80	3.369	2.3899	42	1.41	0.166
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-0.418	3.3799	42	-0.124	0.9022
Irrigation 75%: Fertilizer 80%: Polymer 36.08	0.032	3.3799	42	0.009	0.9925
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-4.8822	3.3799	42	-1.445	0.156
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.2808	0.5299			
Main Plot (rep:irrigation)	1.045	1.0223			
Residual (Error)	0.2808	0.5299			

Table footnote: Significance codes: 0 ***" 0.001*** *" 0.01* " 0.05. rep:irrigation represents the error term for the main plot

Table A.8. Estimates of fixed effects and variance components for the effects random effects of the mixed linear model for efficient use of nitrogen fertilizer (UEFN), expressed in kg/kg. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	28.952	1.3275	42.7962	21.81	< 2e-16 ***
Irrigation 75%	-5.2332	1.8202	37.7113	-2.875	0.0066 **
Fertilization 80%	-7.914	1.766	42	-4.481	0.0000562 ***
Polymer 18.08	-4.2487	1.766	42	-2.406	0.0206 *
Polymer 36.08	-2.8575	1.766	42	-1.618	0.1131
Polymer 52.80	-3.6295	1.766	42	-2.055	0.0461 *
Irrigation 75%: Fertilizer 80%	0.256	2.4975	42	0.103	0.9188
Irrigation 75%: Polymer 18.08	3.0427	2.4975	42	1.218	0.2299
Irrigation 75%: Polymer 36.08	1.1927	2.4975	42	0.478	0.6354
Irrigation 75%: Polymer 52.80	3.1632	2.4975	42	1.267	0.2123
Fert 80%: Polymer 18.08	2.21	2.4975	42	0.885	0.3812
Fert 80%: Polymer 36.08	2,793	2.4975	42	1,118	0.2698
Fert 80%: Polymer 52.80	3.9597	2.4975	42	1.586	0.1204
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-1.158	3.5319	42	-0.328	0.7446
Irrigation 75%: Fertilizer 80%: Polymer 36.08	-0.5575	3.5319	42	-0.158	0.8753
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-5.0937	3.5319	42	-1.442	0.1567
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.2808	0.5299			
Main Plot (rep:irrigation)	1.045	1.0223			
Residual (Error)	0.2808	0.5299			

Table footnote: Significance codes: 0 ***" 0.001*** *" 0.01* " 0.05. rep:irrigation represents the error term for the main plot

Table A.9. Estimates of fixed effects and variance components for the effects random effects of the mixed linear model for efficient use of phosphorus fertilizer (UEP) expressed in kg/kg. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	17.7845	0.8155	42.8007	21.809	< 2e-16 ***
Irrigation 75%	-3.2148	1.1181	37,715	-2.875	0.0066 **
Fertilization 80%	-4.8613	1.0849	42	-4.481	0.0000563 ***
Polymer 18.08	-2.6098	1.0849	42	-2.406	0.0206 *
Polymer 36.08	-1.7553	1.0849	42	-1.618	0.1132
Polymer 52.80	-2.2293	1.0849	42	-2.055	0.0461 *
Irrigation 75%: Fertilizer 80%	0.1573	1.5342	42	0.102	0.9189
Irrigation 75%: Polymer 18.08	1.8693	1.5342	42	1.218	0.2299
Irrigation 75%: Polymer 36.08	0.733	1.5342	42	0.478	0.6353
Irrigation 75%: Polymer 52.80	1.9433	1.5342	42	1.267	0.2123
Fert 80%: Polymer 18.08	1.3573	1.5342	42	0.885	0.3814
Fert 80%: Polymer 36.08	1.7158	1.5342	42	1.118	0.2698
Fert 80%: Polymer 52.80	2.4325	1.5342	42	1.585	0.1204
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-0.7113	2.1697	42	-0.328	0.7447
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-0.343	2.1697	42	-0.158	0.8751
Irrigation 75%: Fertilizer 80%: Polymer 52.80	-3.1295	2.1697	42	-1.442	0.1566
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.1595	0.3994			
Main Plot (rep:irrigation)	0.1466	0.3829			
Residual (Error)	2.3538	1.5342			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.10. Estimates of fixed effects and variance components for the random effects of the mixed linear model for efficient use of potassium fertilizer (UEFK), expressed in kg/kg. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr((>t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	44.4615	2.0387	42.7964	21.809	< 2e-16 ***
Irrigation 75%	-8.0362	2.7953	37.7126	-2.875	0.00661 **
Fertilization 80%	-12.1532	2.7121	42	-4.481	0.0000563 ***
Polymer 18.08	-6.525	2.7121	42	-2.406	0.02061 *
Polymer 36.08	-4.388	2.7121	42	-1.618	0.11316
Polymer 52.80	-5.5737	2.7121	42	-2.055	0.04612 *
Irrigation 75%: Fertilizer 80%	0.3925	3.8354	42	0.102	0.91898
Irrigation 75%: Polymer 18.08	4.6727	3.8354	42	1.218	0.22991
Irrigation 75%: Polymer 36.08	1.8312	3.8354	42	0.477	0.63551
Irrigation 75%: Polymer 52.80	4.8577	3.8354	42	1.267	0.2123
Fert 80%: Polymer 18.08	3.3942	3.8354	42	0.885	0.38121
Fert 80%: Polymer 36.08	4.2887	3.8354	42	1.118	0.26984
Fert 80%: Polymer 52.80	6.0812	3.8354	42	1.586	0.12034
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-1.779	5.4241	42	-0.328	0.74456
Irrigation 75%: Fertilizer 80%: Polymer 36.08	-0.8557	5.4241	42	-0.158	0.8754
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-7.823	5.4241	42	-1.442	0.15665
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.9975	0.9988			
Main Plot (rep:irrigation)	0.9165	0.9573			
Residual (Error)	14.7106	3.8354			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.11. Estimates of fixed effects and variance components for the random effects of the mixed linear model for efficient use of calcium fertilizer (UEFCa), expressed in kg/kg. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	5.16975	0.23703	42.81329	21.811	< 2e-16 ***
Irrigation 75%	-0.934	0.32501	37.72618	-2.874	0.00663 **
Fertilization 80%	-1.413	0.31536	42.00003	-4.481	0.0000564 ***
Polymer 18.08	-0.7585	0.31536	42.00003	-2.405	0.02065 *
Polymer 36.08	-0.51025	0.31536	42.00003	-1.618	0.11315
Polymer 52.80	-0.648	0.31536	42.00003	-2.055	0.04615 *
Irrigation 75%: Fertilizer 80%	0.04525	0.44599	42.00003	0.101	0.91967
Irrigation 75%: Polymer 18.08	0.54275	0.44599	42.00003	1.217	0.23041
Irrigation 75%: Polymer 36.08	0.21275	0.44599	42.00003	0.477	0.63581
Irrigation 75%: Polymer 52.80	0.56425	0.44599	42.00003	1.265	0.21278
Fert 80%: Polymer 18.08	0.3945	0.44599	42.00003	0.885	0.38143
Fert 80%: Polymer 36.08	0.49875	0.44599	42.00003	1.118	0.26979
Fert 80%: Polymer 52.80	0.707	0.44599	42.00003	1.585	0.12041
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-0.20625	0.63072	42.00003	-0.327	0.74529
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-0.0995	0.63072	42.00003	-0.158	0.8754
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-0.909	0.63072	42.00003	-1.441	0.15694

Random Effects	**Variance**	**Standard Deviation (SD)**
Replication (rep)	0.01346	0.116
Main Plot (rep:irrigation)	0.01236	0.1112
Residual (Error)	0.1989	0.446

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.12. Estimates of fixed effects and variance components for the random effects of the mixed linear model for efficient use of magnesium fertilizer (UEFMg), expressed in kg/kg. Pabellón Experimental Field. 2026.

Fixed Effects	Estimate	Std. Error	df	t-value	Pr(>(t))
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	3.102	0.1422	42.7836	21.81	< 2e-16 ***
Irrigation 75%	-0.5607	0.195	37.6972	-2.875	0.0066 **
Fertilization 80%	-0.848	0.1892	42	-4.482	0.0000561 ***
Polymer 18.08	-0.455	0.1892	42	-2.405	0.0207 *
Polymer 36.08	-0.3063	0.1892	42	-1.619	0.113
Polymer 52.80	-0.389	0.1892	42	-2.056	0.046 *
Irrigation 75%:Fertilizer 80%	0.0275	0.2676	42	0.103	0.9186
Irrigation 75%: Polymer 18.08	0.3257	0.2676	42	1.218	0.2302
Irrigation 75%: Polymer 36.08	0.128	0.2676	42	0.478	0.6348
Irrigation 75%: Polymer 52.80	0.339	0.2676	42	1.267	0.2121
Fert 80%: Polymer 18.08	0.2365	0.2676	42	0.884	0.3818
Fert 80%: Polymer 36.08	0.2993	0.2676	42	1.118	0.2697
Fert 80%: Polymer 52.80	0.4245	0.2676	42	1.587	0.1201
Irrigation 75%: Fertilizer 80%: Polymer 18.08	-0.1235	0.3784	42	-0.326	0.7458
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-0.06	0.3784	42	-0.159	0.8748
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-0.546	0.3784	42	-1.443	0.1564
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0.004858	0.0697			
Main Plot (rep:irrigation)	0.004473	0.06688			
Residual (Error)	0.071586	0.26756			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.13. Estimates of fixed effects and variance components for the random effects of the mixed-effects linear model for equatorial diameter (ED) expressed in cm. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Weed Control 0]	17.7	0.5547	27.1671	31.906	<2e-16 ***
Irrigation 75%	-1.925	0.7497	19.9494	-2.568	0.0184 *
Fertilization 80%	-1.625	0.648	42	-2.508	0.0161 *
Polymer 18.08	-0.95	0.648	42	-1.466	0.1501
Polymer 36.08	-0.475	0.648	42	-0.733	0.4676
Polymer 52.80	-0.725	0.648	42	-1.119	0.2696
Irrigation 75%: Fertilizer 80%	1.225	0.9165	42	1.337	0.1885
Irrigation 75%: Polymer 18.08	0.9	0.9165	42	0.982	0.3317
Irrigation 75%: Polymer 36.08	1.3	0.9165	42	1.418	0.1634
Irrigation 75%: Polymer 52.80	1.05	0.9165	42	1.146	0.2584
Fert 80%: Polymer 18.08	0.375	0.9165	42	0.409	0.6845
Fert 80%: Polymer 36.08	1.275	0.9165	42	1.391	0.1715
Fert 80%: Polymer 52.80	1.075	0.9165	42	1.173	0.2474
Irrigation 75%: Fertilizer 80%: Polymer 18.08	0.5	1.2961	42	0.386	0.7016
Irrigation 75%: Fertilizer 80%: Polymer 36.08	-2.5	1.2961	42	-1.929	0.0605
Irrigation 75%: Fertilizer 80%: Polymer 52.80	-2.125	1.2961	42	-1.64	0.1086

Random Effects	**Variance**	**Standard Deviation (SD)**
Replication (rep)	0.1069	0.327
Main Plot (rep:irrigation)	0.2841	0.5331
Residual (Error)	0.8399	0.9165

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.14. Estimates of fixed effects and variance components for the random effects of the mixed-effects linear model for the average weight per head of lettuce (PPPC) expressed in grams. Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	721.02	49.55	35.1	14.551	<2e-16 ***
Irrigation 75%	-113.4	66.24	33.2	-1.712	0.0962
Fertilization 80%	-166.88	62.73	42	-2.66	0.011 *
Polymer 18.08	-94.65	62.73	42	-1.509	0.1388
Polymer 36.08	-108.12	62.73	42	-1.724	0.0921
Polymer 52.80	-95.9	62.73	42	-1.529	0.1338
Irrigation 75%: Fertilizer 80%	54.27	88.71	42	0.612	0.544
Irrigation 75%: Polymer 18.08	26.88	88.71	42	0.303	0.7634
Irrigation 75%: Polymer 36.08	54.88	88.71	42	0.619	0.5395
Irrigation 75%: Polymer 52.80	81.38	88.71	42	0.917	0.3642
Fert 80%: Polymer 18.08	101.17	88.71	42	1.141	0.2605
Fert 80%: Polymer 36.08	105.9	88.71	42	1.194	0.2393
Fert 80%: Polymer 52.80	166	88.71	42	1.871	0.0683 .
Irrigation 75%:Fertilizer 80%:Polymer 18.08	-9.7	125.45	42	-0.077	0.9387
Irrigation 75%:Fertilizer 80%:Polymer 36.08	-57.88	125.45	42	-0.461	0.6469
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-258.52	125.45	42	-2.061	0.0456 *
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	1045.9	32.34			
Main Plot (rep:irrigation)	906.6	30.11			
Residual (Error)	7,869.4	88.71			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.15. Estimates of fixed effects and variance components for the random effects of the mixed linear model for the number of lettuce heads harvested (CABCOS). Pabellón Experimental Field. 2026.

Fixed Effects	**Estimate**	**Std. Error**	**df**	**t-value**	**Pr(>(t))**
(Intercept) [Irrigation 100%, Fertilizer 100%, Pol 0]	69266	4625.59	42.79	14.975	<2e-16 ***
Irrigation 75%	-2124	6,541.57	42.79	-0.325	0.747
Fertilization 80%	-2,701.5	6,094.98	42	-0.443	0.66
Polymer 18.08	-4,620.75	6094.98	42	-0.758	0.453
Polymer 36.08	-2,750.25	6094.98	42	-0.451	0.654
Polymer 52.80	-490	6094.98	42	-0.08	0.936
Irrigation 75%: Fertilizer 80%	-11,970	8,619.61	42	-1,389	0.172
Irrigation 75%: Polymer 18.08	-8,726	8,619.61	42	-1.012	0.317
Irrigation 75%: Polymer 36.08	-6,085.75	8,619.61	42	-0.706	0.484
Irrigation 75%: Polymer 52.80	553.25	8619.61	42	0.064	0.949
Fert 80%: Polymer 18.08	1963	8619.61	42	0.228	0.821
Fert 80%: Polymer 36.08	2787	8619.61	42	0.323	0.748
Fert 80%: Polymer 52.80	-3257.25	8619.61	42	-0.378	0.707
Irrigation 75%: Fertilizer 80%: Polymer 18.08	15,834.25	12,189.97	42	1,299	0.201
Irrigation 75%: Fertilizer 80%: Polymer 36.08	11,399	12,189.97	42	0.935	0.355
Irrigation 75%:Fertilizer 80%:Polymer 52.80	-5,246.75	12,189.97	42	-0.43	0.669
Random Effects	**Variance**	**Standard Deviation (SD)**			
Replication (rep)	0	0			
Main Plot (rep:irrigation)	11286618	3360			
Residual (Error)	74297676	8620			

Table footnote: Significance codes: 0***, 0.001***, *0.01*, 0.05. rep:irrigation represents the error term for the main plot

Table A.16. Irrigation volume applied to the treatment of 75% of water requirements in lettuce. Pabellón Experimental Field. 2026.

		PABELLÓN EXPERIMENTAL FIELD, NORTH-CENTRAL CIR					
		IRRIGATION RECORD FORMAT FOR THE 2026 POLYMERS TRIAL					
		75% WATER REQUIREMENTS					
		Area	4365	m^2	0.4365	hectares	
No.	**DATE**	**IRRIGATION DURATION IRRIGATION (h)**	**IRRIGATION TIME**		**METER**		**VOLUME**
			START	**END**	**START**	**END**	
1	March 9, 2026	10:45	11:30	09:57	42017.046	42185.562	168,516
2	March 10, 2026	1.08	12:10	1:15 p.m.	42,185.568	42,209.246	23,678
3	March 10, 2026	2.18	4:30 p.m.	6:41 PM	42,209.246	42,276.47	67,224
4	March 11, 2026	0.92	12:45	1:40 p.m.	42,276.47	42,316.511	40,041
5	March 16, 2026	1.75	2:07 p.m.	3:52 p.m.	42,757.038	42,802.14	45,102
6	March 19, 2026	0.93	12:04	1:00 PM	42,858.976	42,890.172	31,196
7	March 23, 2026	1.43	11:13	12:39	42,929.76	42,970.688	40,928
8	March 26, 2026	1.28	1:47 p.m.	3:04 p.m.	43,629.906	43,668.757	38,851
9	March 30, 2026	1.62	10:40	12:17	43,993.839	44,036.169	42.33
10	April 6, 2026	2.48	3:20 p.m.	5:49 PM	44,194.406	44,262.096	67.69
11	April 9, 2026	1.52	2:33 p.m.	4:04 p.m.	44,333.24	44,383.287	50,047
12	April 13, 2026	2.10	3:50 p.m.	5:56 p.m.	45,055.229	45,138.751	83,522
13	April 17, 2026	1.82	12:58	2:47 p.m.	45,375.122	45,446.505	71,383
14	April 20,	2.37	4:02 p.m.	6:22 PM	45,572.571	45,625.157	52,586

	2026						
15	April 23, 2026	1.85	3:05 p.m.	4:56 p.m.	45,700.395	45,757.8	57,405
16	April 27, 2026	2.97	10:27	1:25 p.m.	45,875.155	45,966.154	90.999
17	April 29, 2026	1.68	10:08	11:49	46,095.418	46,147.19	51,772
18	May 1, 2026	1.62	09:59	11:36	46,253.138	46,302.251	49,113
19	May 4, 2026	2.38	1:20 p.m.	3:43 p.m.	46,369.121	46,442.935	73,814
20	May 5, 2026	3.38	6:29 PM	9:52 PM	46,625.045	46,695.042	69,997
Total per plot (h)		**45.82**			**Volume per plot (m^3)**		**1,216.194**
Total per ha (h)		**104.96**			**Volume per hectare (m^3)**		**2,786.241**

Note: The first irrigation in the table corresponds to the planting irrigation and was applied starting on March 9, 2026, at 10:45 p.m. and concluded on March 10, 2026, at 9:57 a.m., with a flow rate of approximately 3.7 lps for the large plot at 100% of water requirement.

Table A.17. Irrigation volume applied to the 100% water requirement treatment for lettuce. Pabellón Experimental Field. 2026.

		PABELLÓN EXPERIMENTAL FIELD, NORTH-CENTRAL CIR					
		IRRIGATION RECORD FORMAT FOR THE 2026 POLYMERS TRIAL					
		100% WATER REQUIREMENTS					
		Area	4545	m^2	0.4545	hectares	
No.	**DATE**	**IRRIGATION DURATION IRRIGATION (h)**	**IRRIGATION TIME**		**METER**		**VOLUME**
			START	**END**	**START**	**END**	
1	March 9, 2026	10:08	11:30	09:35	41,849.990	42,017.046	167,056
2	March 10, 2026	0.50	11:40	12:10	42017.046	42,027.927	10,881
3	March 10, 2026	2.18	4:30 p.m.	6:41 PM	42,276.470	42,346.437	69,967
4	March 16, 2026	2.15	3:52 PM	4:38 p.m.	42,802.140	42,821.957	19,817
5	March 17, 2026	1.40	3:43 p.m.	5:07 p.m.	42,821.957	42,858.976	37,019
6	March 19, 2026	1.23	2:09 p.m.	3:23 PM	42,890.172	42,929.761	39,589
7	March 23, 2026	1.90	12:39	2:33 p.m.	42,970.688	43,036.589	65,901
8	March 26, 2026	1.78	3:40 p.m.	5:27 p.m.	43,668.757	43,722.706	53,949
9	March 30, 2026	2.25	12:30	2:45 PM	44,036.169	44,092.800	56,631
10	April 6, 2026	3.45	11:41	3:08 p.m.	44,092.800	44,194.406	101,606
11	April 9, 2026	2.08	12:27	2:32 p.m.	44,262.092	44,333.240	71,148
12	April 13, 2026	2.92	12:41	3:36 PM	44,952.687	45,055.729	103,042
13	April 17, 2026	2.53	2:52 PM	5:24 p.m.	45,405.721	45,493.828	88,107
14	April 20, 2026	3.28	12:36	3:53 p.m.	45,493.828	45,572.571	78,743

15	April 23, 2026	2.57	12:29	3:03 p.m.	45,625.157	45,700.375	75,218
16	April 27, 2026	4.12	1:30 PM	5:37 p.m.	45,966.154	46,095.418	129,264
17	April 29, 2026	2.32	12:05	2:24 p.m.	46,147.190	46,253.138	105,948
18	May 1, 2026	2.23	11:39	1:54 p.m.	46,302.251	46,369.121	66,870
19	May 4, 2026	3.32	09:55	1:14 p.m.	46,442.935	46,535.882	92,947
20	May 6, 2026	3.15	7:21 p.m.	10:30 p.m.	46,695.048	46,760.223	65.175
Total per plot (h)		**55.45**			**Volume per plot (m^3)**		**1,498.878**
Total per ha (h)		**122.00**			**Volume per hectare (m^3)**		**3,297.861**

Note: The first irrigation in the table corresponds to the planting irrigation and was applied starting on March 9, 2026, at 11:30 p.m. and concluded on March 10, 2026, at 9:35 a.m., with a flow rate of approximately 3.7 lps for the large plot at 100% of water requirement.

Table A.18. Polymer doses applied to the lettuce experiment. Pabellón Experimental Field. 2026.

Treatments	Polymer Level (kg/ha)	Fertilization Level (%)	Water Level (%)	AREA/TREATMENT (m^2)	POLYMER PER TREATMENT (kg)	POLYMER PER REPETITION (kg)	POLYMER PER 25-METER GROOVE (g)	POLYMER PER LINEAR METER (g)
Treatment 1	0	80	75	540	0	0	0	
Treatment 2	0	80	100	540	0	0	0	
Treatment 3	0	100	75	540	0	0	0	
Treatment 4	0	100	100	540	0	0	0	
Treatment 5	18.08	80	75	540	0.97632	0.24408	40.68	1.6272
Treatment 6	18.08	80	100	540	0.97632	0.24408	40.68	1.6272
Treatment 7	18.08	100	75	540	0.97632	0.24408	40.68	1.6272
Treatment 8	18.08	100	100	540	0.97632	0.24408	40.68	1.6272
Treatment 9	36.08	80	75	540	1.94832	0.48708	81.18	3.2472
Treatment 10	36.08	80	100	540	1.94832	0.48708	81.18	3.2472
Treatment 11	36.08	100	75	540	1.94832	0.48708	81.18	3.2472
Treatment 12	36.08	100	100	540	1.94832	0.48708	81.18	3.2472
Treatment 13	52.8	80	75	540	2.8512	0.7128	118.8	4,752
Treatment 14	52.8	80	100	540	2.8512	0.7128	118.8	4,752
Treatment 15	52.8	100	75	540	2.8512	0.7128	118.8	4,752
Treatment 16	52.8	100	100	540	2.8512	0.7128	118.8	4,752

Table A.19. Irrigation water fertilization scheme for treatments with 75% irrigation and 100% fertilization in lettuce. Pabellón Experimental Field. 2026.

Date	Ammonium Nitrate (kg)	Monoammonium Phosphate (kg)	Potassium Nitrate (kg)	Potassium Sulfate (kg)	Calcium Nitrate (kg)	Magnesium Sulfate (kg)	Soluble Micronutrients (g)
March 19, 2026	1,621	0.641	2.183	0.000	0.000	0.000	49,846
March 23, 2026	1,563	0.962	2,619	0.000	0.000	0.000	49,846
March 26, 2026	2,448	0.962	3,056	0.000	0.000	0.000	49,846
March 30, 2026	2,391	1,282	3,493	0.000	0.000	0.000	49,846
April 2, 2026	3,147	1,282	4,366	0.000	0.926	2,755	49,846
April 6, 2026	4,768	1,923	6,549	0.000	0.926	2,755	49,846
April 9, 2026	5,593	1,923	6,549	0.000	1,852	2,755	49,846
April 13, 2026	6,981	2,564	0.000	8,836	1,852	4,133	49,846
April 16, 2026	7,806	2,564	0.000	8,836	2,779	4,133	49,846
April 20, 2026	8,679	3,206	0.000	10,041	2,779	4,133	49,846
April 23, 2026	8,585	3,206	0.000	10,041	3,705	5,510	49,846
April 27, 2026	6,793	2,564	0.000	6,025	3,705	4,133	49,846
April 30, 2026	2,477	1,282	0.000	4,016	1,852	2,755	49,846
TOTAL	**62,851**	**24,362**	**28,814**	**47,796**	**20,377**	**33,061**	**648,000**

Note: Large plot size (irrigation) 75% = 0.2160 ha and includes the two medium-sized plots with 100% fertilization.

Table a.20. Fertilization scheme via irrigation water for treatments with 75% irrigation and 80% fertilization in lettuce. Pabellón Experimental Field. 2026.

Date	Ammonium Nitrate (kg)	Monoammonium Phosphate (kg)	Potassium Nitrate (kg)	Potassium Sulfate (kg)	Calcium Nitrate (kg)	Magnesium Sulfate (kg)	Soluble Micronutrients (g)
March 19, 2026	1,301	0.513	1,746	0.000	0.000	0.000	39,877
March 23, 2026	1,255	0.769	2,096	0.000	0.000	0.000	39,877
March 26, 2026	1,965	0.769	2,445	0.000	0.000	0.000	39,877
March 30, 2026	1,919	1,026	2,794	0.000	0.000	0.000	39,877
April 2, 2026	2,526	1,026	3,493	0.000	0.741	2,204	39,877
April 6, 2026	3,827	1,539	5,239	0.000	0.741	2,204	39,877
April 9, 2026	4,489	1,539	5,239	0.000	1,482	2,204	39,877
April 13, 2026	5,601	2,052	0.000	7,069	1,482	3,306	39,877
April 16, 2026	6,264	2,052	0.000	7,069	2,223	3,306	39,877
April 20, 2026	6,964	2,564	0.000	8,033	2,223	3,306	39,877
April 23, 2026	6,889	2,564	0.000	8,033	2,964	4,408	39,877
April 27, 2026	5,451	2,052	0.000	4,820	2,964	3,306	39,877
April 30, 2026	1,988	1,026	0.000	3,213	1,482	2,204	39,877
TOTAL	**50,439**	**19,490**	**23,051**	**38,236**	**16,302**	**26,449**	**518,400**

Note: Large plot size (irrigation) 75% = 0.2160 ha and includes the two medium-sized plots with 80% fertilization.

Table a.21. Fertilization schedule via irrigation water for treatments with 100% irrigation and 100% fertilization in lettuce. Pabellón Experimental Field. 2026.

Date	Ammonium Nitrate (kg)	Monoammonium Phosphate (kg)	Potassium Nitrate (kg)	Potassium Sulfate (kg)	Calcium Nitrate (kg)	Magnesium Sulfate (kg)	Soluble Micronutrients (g)
March 19, 2026	1,708	0.681	2,319	0	0.000	0.000	52,962
March 23, 2026	1,643	1,022	2,783	0	0.000	0.000	52,962
March 26, 2026	2,581	1,022	3,247	0	0.000	0.000	52,962
March 30, 2026	2,516	1,362	3,711	0	0.000	0.000	52,962
April 2, 2026	3,309	1,362	4,639	0	0.984	2,927	52,962
April 6, 2026	5,016	2,044	6,958	0	0.984	2,927	52,962
April 9, 2026	5,887	2,044	6,958	0	1,968	2,927	52,962
April 13, 2026	7,392	2,725	0.000	9,388	1,968	4,391	52,962
April 16, 2026	8,263	2,725	0.000	9,388	2,952	4,391	52,962

April 20, 2026	9,187	3,406	0.000	10,669	2,952	4,391	52,962
April 23, 2026	9,081	3,406	0.000	10,669	3,937	5,855	52,962
April 27, 2026	7,180	2,725	0.000	6,401	3,937	4,391	52,962
April 30, 2026	2,613	1,362	0.000	4,267	1,968	2,927	52,962
TOTAL	**66,375**	**25,885**	**30,614**	**50,783**	**21,651**	**35,128**	**688,500**

Note: Large plot size (irrigation) 100% = 0.2295 ha and includes the two medium-sized plots with 100% fertilization.

Table A.22. Fertilization scheme via irrigation water for treatments with 100% irrigation and 80% fertilization in lettuce. Pabellón Experimental Field. 2026.

Date	Ammonium Nitrate (kg)	Monoammonium Phosphate (kg)	Potassium Nitrate (kg)	Potassium Sulfate (kg)	Calcium Nitrate (kg)	Magnesium Sulfate (kg)	Soluble Micronutrients (g)
March 19, 2026	1,370	0.545	1,855	0.000	0.000	0.000	42,369
March 23, 2026	1,319	0.817	2,227	0.000	0.000	0.000	42,369
March 26, 2026	2,071	0.817	2,598	0.000	0.000	0.000	42,369
March 30, 2026	2,019	1,090	2,969	0.000	0.000	0.000	42,369
April 2, 2026	2,656	1,090	3,711	0.000	0.787	2,342	42,369
April 6, 2026	4,027	1,635	5,566	0.000	0.787	2,342	42,369
April 9, 2026	4,725	1,635	5,566	0.000	1,575	2,342	42,369
April 13, 2026	5,932	2,180	0.000	7,511	1,575	3,513	42,369
April 16, 2026	6,630	2,180	0.000	7,511	2,362	3,513	42,369
April 20, 2026	7,372	2,725	0.000	8,535	2,362	3,513	42,369
April 23, 2026	7,287	2,725	0.000	8,535	3,149	4,684	42,369
April 27, 2026	5,762	2,180	0.000	5,121	3,149	3,513	42,369
April 30, 2026	2,097	1,090	0.000	3,414	1,575	2,342	42,369
TOTAL	**53,268**	**20,708**	**24,492**	**40,626**	**17,321**	**28,102**	**550,800**

Note: Large plot size (irrigation) 100% = 0.2295 ha and includes the two medium-sized plots with 80% fertilization.

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