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sprouting; 2) emergence; 3) start of stolonization; 4) stolon elongation; 5) start of tuberization (diameter >1 cm); 6) tuber development (diameter from 3 to 5 cm); 7) developed tubers (diameter >5 cm); 8) foliage killing (complete skin) (diameter from 7 to 8 cm); and 9) harvest.

GDDs were accumulated for each development phase using the mean daily air temperature (Ta) from an automated weather station (AWS) located 100 m from the experimental lot. GDDs were calculated with the method reported by Ojeda *et al*. (2004) in potato crop studies in Sinaloa, using 2 and 29 °C as minimum and maximum development threshold temperatures.

Soil moisture was also monitored biweekly in the two upper strata (0-30 and 30-60 cm) with a Spectrum 300 time-domain reflectometry (TDR)-type portable moisture sensor manufactured in Illinois, USA, and calibrated for the study area.

The killing of foliage was carried out using contact herbicide Velquat 25 (ai. Paraquat) on 10/02/2016 at 1 754 AGDDs, while the harvest was carried out on 11/03/2016 at 2 282 AGDDs once the tuber skin had the appropriate consistency. The tubers were extracted from the soil mechanically by tractor, using 18-inch moldboards mounted on a horizontal support bar. After the killing of foliage, in each experimental plot, the tubers that remained within an area of 9 m^2 (useful plot) formed of the two central beds 5 m long (2 x 0.9 x 5 m) were collected and weighed manually.

The samples obtained were determined the variables Y, relative yield (RY), and quality; the first calculated with equation (4):

$$Y=\frac{Ws \times 10}{9}$$

Where: Ws= represents the weight of the sample expressed in kg, Y= in t ha^{-1} and the constants 10 and 9 are constants for unit conversion. RY of each variety was calculated with respect to the yield of the treatment with low water deficit, expressed as a percentage.

To analyze the quality of tubers, the different qualities were separated considering the equatorial diameter (mm), according to the criteria of the area (Table 2) and it was expressed in terms of percentage with respect to the total yield. Camargo *et al*. (2015) used a similar methodology grouping three categories, specifying that tubers of 40 to 80 mm in diameter are the most commercialized, which coincides with the classification of the study area. In addition to the equatorial diameter, deformed (DEF) and diseased (NCO) tubers were separated.

Table 2. Classification of potato tubers based on equatorial diameter used in northern Sinaloa, Mexico.

Quality	Code	Diameter (mm)
First	Q1	71-80
Second	Q2	51-70
Third	Q3	41-50
Fourth	Q4	31-40
Fifth	Q5	21-30
Giant	GIA	>80
Deformed	DEF	-
Noncommercial	NCO	-

For the statistical analysis, the SAS online version (www.sas.com/es-mx/software/on-demand-for-academics.htm) computer program was used, with which an analysis of variance of the variables yield (Y) and quality (Q) was carried out, considering the simple effects and the interaction of the factors water stress and varieties, in addition to a comparison of means with Tukey’s test (*p*≤ 0.05). The model used is shown in equation (6) (Fernández *et al*., 2010).

$$Y_{ijr} - \mu = \rho_r + \alpha_i + \varepsilon_{jr} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijr}$$

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Where: Y_{ijr} - μ= represents the deviation of an observation from the global mean (μ); ρ_r= are the deviations caused by the blocks; α_i= is the main factor; β_j= is the subordinate factor; $(\alpha\beta)_{ij}$= is the interaction between factors; and ε_{jr} and ε_{ijr}= are random errors. For the quality variable, an analysis of the distribution of each classification by variety was carried out to know the effect of water deficit on this important variable.

Results and discussion

Yield and quality

Table 3 shows the analysis of variance of variables Y and Q of the two factors studied. The analysis shows a significant effect (Tukey, $p \leq 0.05$) of the water deficit factor only for the variable Y; the results showed a reduction of up to 3.65 t ha^{-1} of the variable Y in the treatment with high water deficit compared to the low deficit, which is consistent with what was reported by Steduto *et al*. (2012); Mahima *et al*. (2018).

Table 3. Analysis of significance of yield (Y) and quality (Q) of three potato varieties subjected to three levels of water deficit.

Treatments		Y (t ha^{-1})	Q1	Q2	Q3	Q4	Q5	DEF	NCO
					Water deficit				
	Low	26.45	2.61	4.56	5.21	6.19	5.08	1.03	1.76
	Medium	24.99	2.04	4.06	5.27	5.92	4.64	1.88	1.17
	High	22.8	1.96	3.5	4.96	4.01	5.48	1.66	1.24
Tukey ($p \leq 0.05$)		s	ns	ns	ns	ns	ns	ns	ns
					Varieties				
	Fiana	26.14	3.09	5.29	5.23	4.14	5.88	1.49	1.01
	Ágata	26.45	0.57	3.13	4.93	7.4	6.74	1.94	1.75
	Atlantic	21.22	2.99	3.62	5.29	4.44	2.36	1.15	1.38
Tukey ($p \leq 0.05$)		s	s	s	ns	s	s	ns	ns
					Water deficit x variety interaction				
Low	Fiana	30.29	3.5	6.64	5.96	4.65	6.77	1.2	1.58
	Ágata	26.11	1.23	3.03	4.96	8.6	4.91	1.19	2.2
	Atlantic	21.78	3.26	3.85	4.55	5.02	3.07	0.61	1.41
Medium	Fiana	25.80	2.9	5.03	5.65	4.47	6.06	1.41	0.29
	Ágata	27.83	0.38	3.93	5.23	7.88	5.58	3.1	1.73
	Atlantic	21.34	2.85	3.21	4.94	5.42	2.3	1.13	1.5
High	Fiana	22.33	2.86	4.22	4.08	3.29	4.83	1.87	1.18
	Ágata	25.42	0.1	2.42	4.62	5.71	9.72	1.53	1.33
	Atlantic	20.67	2.92	3.87	6.19	3.02	1.88	1.58	1.22
Tukey ($p \leq 0.05$)		ns	ns	ns	ns	ns	s	ns	ns

Y= yield; Q= quality; DEF= deformed tubers; NCO= noncommercial; s= statistically significant; ns= statistically non-significant (Tukey, $p \leq 0.05$).

Regarding the variety factor, a significant effect was also observed in the variables Y, Q1, Q2, Q4, and Q5; Fiana and Ágata obtained similar yields, with 26.14 and 26.45 t ha^{-1} respectively, while Atlantic obtained 21.22 t ha^{-1}, which represents a difference of 4.92 t ha^{-1}. In this factor, Q1 and Q2 were higher with Fiana, followed by Atlantic and Ágata; Fiana also presented fewer noncommercial tubers.

In the water deficit-variety interaction, significance was found only for the Q5 variable; however, important effects were observed: at the low level of water deficit, Fiana obtained the highest yield

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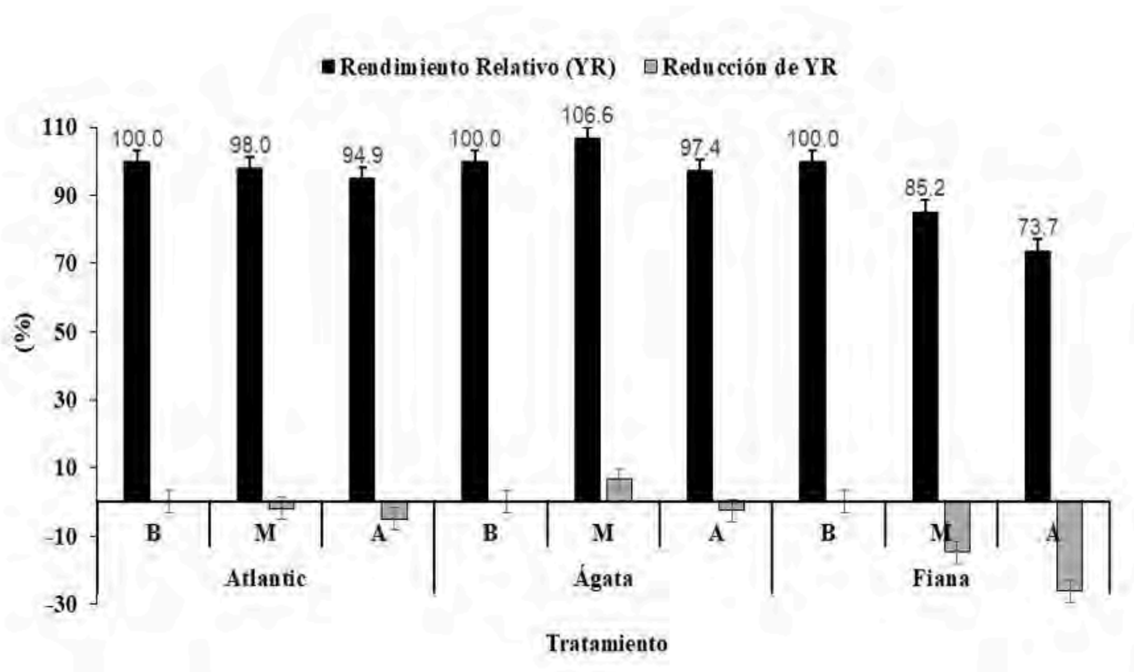
(30.29 t ha^{-1}), with more Q1 and Q2, followed by Ágata and Atlantic, with the latter showing fewer DEF and NCO tubers. At the medium level, Ágata was the best in yield but the lowest in Q1 and highest in DEF and NCO. The behavior was similar at the high level; Ágata was the best in Y but with less Q1 and Q2 and an important presence of DEF and NCO.

Relative yield (RY)

Figure 1 shows the effect of the three levels of water deficit on the RY of each variety (stress level x variety interaction). The results indicate that with the high level of water stress ($\propto_3 = 0.45$), the Fiana variety had the highest RY drop, with 26.3%, followed by Atlantic with 5.1% and Ágata with only 2.8%, compared to the low level, and tendency not to affect the yield at the medium level. This indicates that the Fiana variety is the most sensitive to water deficit, while Ágata is the most tolerant, Atlantic can be considered of intermediate sensitivity.

Figure 1. Relative yield (RY) in three potato varieties subjected to three levels of water deficit. B= low deficit (L); M= medium deficit; A= high deficit (H) in northern Sinaloa, Mexico.



Studies such as those by Da Silva *et al*. (2019) reported a similar behavior regarding the Ágata variety, concluding that the best management conditions were obtained when applying intermediate irrigation sheets (27 mm between irrigations).

Quality distribution

An important effect of water deficit on this variable was found in each variety (Figure 2), as reported by Jha *et al*. (2017). At the low deficit level, the Atlantic variety produced the largest number of Q1 and Q2 tubers, with 15 and 18% of total production, respectively. The high and medium deficits generated the highest values of Q3 tubers, with 30 and 23%, while the highest value of Q4 tubers was obtained with the medium level of water deficit.

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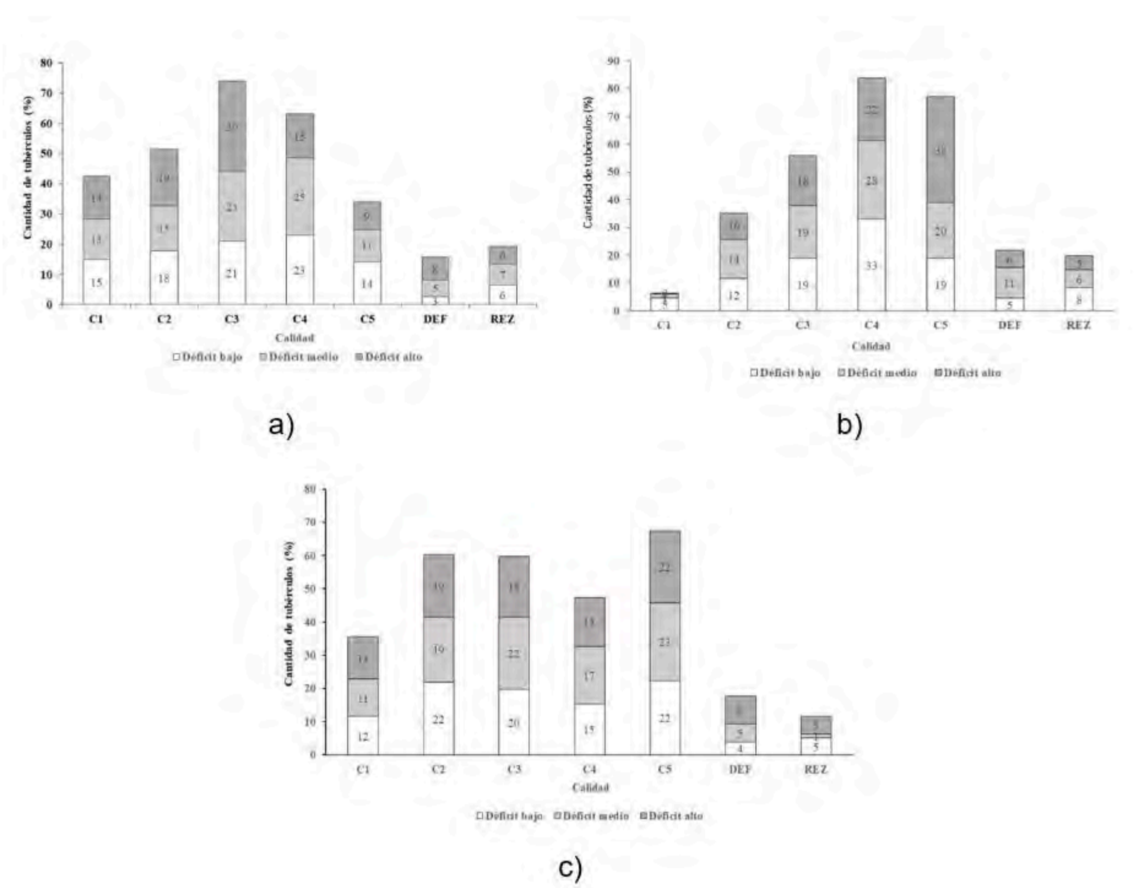
Figure 2. Distribution of the quality of the tuber production of potato varieties Atlantic. a) Ágata; b) Fiana and c) subjected to three levels of water deficit in northern Sinaloa, Mexico.



The Q5 tubers remained around 10% in the three levels of water deficit due to their little development due to the advance to harvest induced through the defoliant. Similarly, for the Ágata variety, the highest percentages of Q1 and Q2 tubers were generated with the low level of water deficit (5 and 12%, respectively), maintaining similar values in the Q3 tubers in the three levels of deficit (18 to 19%).

A significant increase in Q4 and Q5 tubers was analyzed in the three deficit levels, mainly with the high value, which induced the production of 38% of Q5 tubers. The high values of Q4 and Q5 tubers could also be due to the slower development of this variety compared to the others. This confirms that the values of parameter $\propto_3$ are associated with the irrigation system; the values vary from 0.15 to 0.3 for drip irrigation, from 0.4 to 0.55 for sprinkler irrigation, and they were greater than 0.6 for gravity irrigation (Ojeda *et al*., 2004).

Regarding the Fiana variety, the highest values of Q1 tubers were similar in the three levels of water deficit, with percentages of 11 to 13%, while the highest values of Q2 tubers occurred with the low level of deficit, with 22%. The Q3, Q4, and Q5 tubers presented similar increases in the three stress levels; although the higher percentage was more frequent with the medium level of water deficit in the three qualities, a behavior similar to the other varieties.

With regard to DEF tubers, a direct relationship with water deficit was examined in all three varieties; that is, when this increases, the proportion of this class of tubers increases, as mentioned by Steduto *et al*. (2012), it reached values close to 10% of production with the high and medium level of deficit.

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In the NCO, a tendency towards an increase with the low level of water deficit was found in the three varieties, which may be associated with a more humid environment generated by the low permeability of the soil, Wagg *et al*. (2021) suggest high levels of moisture in well-drained soils, since heavy and frequent irrigation in soils with low permeability favors the development of pathogens, mainly fungi and bacteria (Rich, 1983). With the medium and high deficit levels, the tendency was towards decreasing NCO, so in practice, the different stress management scenarios should be analyzed according to the objectives of each producer.

Water use efficiency

Table 4 presents a summary of applied supplemental irrigations generated with the three levels of water deficit. It was perceived that 14 supplemental irrigations with a maximum interval of 22 days and a minimum of five days were generated for the low level; eight supplemental irrigations with a maximum interval of 30 days and a minimum of eight days were applied with the medium level of deficit.

Table 4. Summary of supplemental irrigation applied in three levels of water deficit (MAD) in potato crops, generated with the Irrimodel platform (Sifuentes and Macías, 2015).

Water deficit (MAD)	Supplemental irrigations applied	Maximum interval (days)	Minimum interval (days)	Net sheet (cm)	Gross sheet (cm)	Application efficiency (%)
L (0.15)	14	22	5	29.5	32.5	90.6
M (0.3)	8	30	8	28.8	32	90
H (0.45)	5	36	13	28.4	34.8	81.5

L= low deficit; M= medium deficit; H= high deficit.

On the other hand, with the high level, the maximum and minimum intervals were 36 and 13 days, respectively. Regarding the irrigation requirements or Sn, the low level had a value of 29.5 cm, higher than the medium and high levels, due to the lower level of stress to which the crop was subjected, which affects evapotranspiration.

A higher value of AE was also observed at the low and medium levels, with values of 90.6 and 90%, respectively, while at the high level of stress, it was 81.5% because of the reduction of Sn due to the high stress considered in the ETc calculations and the greater Sb derived from a longer irrigation time used in the formation of the wet bulb.

Regarding WP, it was found that with the low level of water deficit, the varieties Atlantic and Fiana obtained the highest values, with 6.7 and 9.32 kg m^{-3}, respectively, while for Ágata, the highest values were similar at the low and medium levels, with 8.03 and 8.7, which indicates some resistance to water stress. In all cases, the values are in the range reported by Erdem *et al*. (2006); Steduto *et al*. (2012); Mahima *et al*. (2018).

Conclusions

The Fiana variety was the most sensitive to water deficit from the point of view of yield, followed by Atlantic and Ágata. Applying irrigation intervals, sheets, and AE recommended by the Irrimodel Software was very convenient in all cases. The effect of water deficit on tuber size was different for each variety due to their specific development pattern and tolerance to water stress.

As the water deficit increased ($\propto_3$ high), associated with a longer irrigation interval, the proportion of deformed tubers increased, while diseased and noncommercial tubers increased with the low deficit ($\propto_3$ low), so conditions of excess moisture should be avoided, mainly in heavy soils and cold climatic conditions.

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The application of the Irrimodel software represents an excellent automated tool for the controlled management of water deficit according to the irrigation system, which translates into the improvement of potato yield and quality for the producing areas of Mexico. For a greater effect of water deficit on yield, it is suggested to use $\propto_3$ values of 0.15, 0.45, and 0.6 for low, medium, and high deficits, which are associated with drip, sprinkler, and gravity irrigation systems, respectively.

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