



CHALQUEÑO MAIZE (*Zea mays* L.) YIELD UNDER DIFFERENT FERTILIZATION SCHEMES IN THE MUNICIPALITY OF APAN, HIDALGO, MEXICO †

[RENDIMIENTO DE MAÍZ CHALQUEÑO (*Zea mays* L.) BAJO DIFERENTES ESQUEMAS DE FERTILIZACIÓN EN EL MUNICIPIO DE APAN, HIDALGO, MÉXICO]

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SUMMARY

Background. In Mexico, corn is the most important crop, being an important input with food, economic, political, and social implications. However, intensive cultivation methods, based on chemical pesticides, monoculture and synthetic agrochemicals have caused a reduction in soil fertility and crop yields. An alternative, which can help restore soil fertility, increasing organic matter, moisture retention and the load of microorganisms, is mixed fertilizer. Stimulating, in addition, the defense systems of the plants and thus increasing the yield of the crops. **Objective.** To evaluate some fertilization schemes in Chalqueño maize plants through the measurement of some growth and yield variables. **Methodology.** A completely randomized block experimental design was established with three repetitions, where four fertilization schemes were evaluated (T1, control without fertilizer input; T2, chemical fertilizer; T3, organic fertilizer; and T4, chemical fertilizer + organic fertilizer) during the crop years 2019-2020. **Results.** The analyzes showed significant differences ($p \leq 0.05$) between the evaluated treatments and years of cultivation. Being the T4 treatment, the one that obtained the best grain yield for the years 2019 and 2020, with values of 5.11 ± 0.05^b t ha⁻¹ and 6.57 ± 0.95^a t ha⁻¹, while the T1 treatment, recorded 1.59 ± 0.12^f t ha⁻¹ and 2.15 ± 0.38^e t ha⁻¹, respectively. **Implications.** With the information generated, it will be possible to implement the best fertilization scheme that provides the corn plants with all the necessary nutrients so that year after year they obtain the best grain yields. **Conclusion.** Through the results it was possible to demonstrate the negative effect of environmental factors (higher temperature and less rainfall), on the yield of the corn crop during the year 2019, with respect to the best yield result obtained for all the treatments during the year 2020 where a lower temperature and higher rainfall were recorded. Being equally evident the positive effect on the yield when plants were fertilized with the T4 treatment that provided to the corn crop with an adequate dose of moisture and macro and micronutrients.

Key words: Corn; chalqueño; vermicompost; chemical fertilizer; mixed fertilizer.

RESUMEN

Antecedentes. En México, el maíz es el cultivo más importante, siendo un insumo importante con implicaciones alimentarias, económicas, políticas y sociales. Sin embargo, los métodos de cultivo intensivos, basados en pesticidas químicos, monocultivos y agroquímicos sintéticos han provocado una reducción en la fertilidad del suelo y el rendimiento de los cultivos. Una alternativa es el fertilizante mixto que permite restaurar la fertilidad del suelo, aumentando la materia orgánica, la retención de humedad y la carga de microorganismos. Además de estimular los sistemas de defensa de las plantas y aumentar el rendimiento de los cultivos. **Objetivo.** Evaluar algunos esquemas de fertilización en plantas de maíz Chalqueño mediante la medición de variables importantes para el crecimiento y

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rendimiento. **Metodología.** Se estableció un diseño experimental en bloques completamente al azar con tres repeticiones, donde se evaluaron cuatro esquemas de fertilización (T1, testigo sin aporte de fertilizante; T2, fertilizante químico; T3, fertilizante orgánico; y T4, fertilizante químico + fertilizante orgánico) durante los años de cultivo 2019-2020. **Resultados.** Los análisis mostraron diferencias significativas ($p \leq 0.05$) entre los tratamientos evaluados y años de cultivo, siendo el tratamiento T4, el que obtuvo el mejor rendimiento de grano para los años 2019 y 2020, con valores de 5.11 ± 0.05^b t ha⁻¹ y 6.57 ± 0.95^a t ha⁻¹, mientras que el tratamiento T1, registró 1.59 ± 0.12^f t ha⁻¹ y 2.15 ± 0.38^e t ha⁻¹, respectivamente. **Implicaciones.** Con la información generada se podrá implementar el mejor esquema de fertilización que proporcione a las plantas de maíz todos los nutrientes necesarios para que año tras año los productores obtengan los mejores rendimientos de grano. **Conclusión.** A través de los resultados se pudo evidenciar el efecto negativo de los factores ambientales (mayor temperatura y menor precipitación), sobre el rendimiento del cultivo de maíz durante el año 2019, con respecto al mejor resultado de rendimiento obtenido para todos los tratamientos durante el año 2020 donde se registró una temperatura menor y una precipitación mayor. Siendo igualmente evidente el efecto positivo en el rendimiento cuando las plantas fueron fertilizadas con el tratamiento T4 que proporcionó al cultivo de maíz una dosis adecuada de humedad, macro y micronutrientes.

Palabras claves: Maíz; chalqueño; lombricomposta; abono químico; abono mixto.

INTRODUCTION

Maize constitutes one of the most important crops for the Mexican population, being cultivated for food purposes in most of the country's states, under a wide range of environmental conditions. Where it is cultivated, from sea level to more than 3400 m, in areas with low or abundant rainfall, with temperate, warm, humid, or tropical climates, on scarce soils, steep slopes or in fertile valleys, during different times of the year (Sierra-Macías *et al.*, 2014). However, unsustainable agricultural practices, land use change as a consequence of urbanization, and climate change are factors that have caused a considerable decrease in maize yields and genetic diversity in the High Valleys (Hernández *et al.*, 2018; CIMMYT, 2022). This region covers part of the states of Mexico, Morelos, Puebla, Tlaxcala, and Hidalgo, between 2,200 and 2,600 masl, a condition that makes it one of the highest altitude regions in the country (Martínez *et al.*, 2018a). In this area, around 3.5 million hectares of corn are cultivated (González *et al.*, 2008), of which 85% is planted under rainfed conditions (Miguel *et al.*, 2004). Being, in addition, one of the important centers in the evolution and domestication of corn (CIMMYT, 2022). Since two of the oldest races of maize (Palomero Toluqueño and Arrocillo Amarillo), the rest of the races that are currently cultivated in central Mexico originated. Of which, in the High Valleys region, the predominant corn is the Chalqueño race (Miguel *et al.*, 2004). Late corn, planted under residual moisture conditions, medium to large ears, conical to pyramidal in shape and dented kernel, with more than 12 rows (Herrera-Cabrera *et al.*, 2004; Aragón *et al.*, 2006; Mota *et al.*, 2020a). Cultivated in geographical regions ranging from 1900 to 2700 masl (Pérez *et al.*, 2007). Creole race that is highly appreciated because they are considered specialty genetic materials and a source of high-yield genes for the creation of hybrids (Mota *et al.*, 2020b; CIMMYT, 2022). Similarly, this corn is preferred by producers due to its adaptation to the region's temporary conditions, as well as its

gastronomic qualities for the preparation of different foods, and for the industrial extraction of pigments (Arellano *et al.*, 2003; López-Morales *et al.*, 2021).

However, due to the abuse of monoculture as the only production system, for more than 40 years, in the municipality of Apan, serious changes have occurred in the texture of the soil, reduction in the levels of organic matter, nitrogen, retention of water and cation exchange (Prieto *et al.*, 2012). Agricultural practices, which ultimately have a negative impact on crop yields. In this sense, the use of organic and low doses of chemical fertilizers allows for improving the physical-chemical properties of soils, and their natural fertility, reducing erosion, improving soil microbiology, and increasing yields (Barrera-Violeth *et al.*, 2017; Solís, 2021; Hernández-Melchor *et al.*, 2022). For this reason, the preservation and improvement of the yields obtained by native maize in Mexico should be key agricultural strategies to strengthen the country's food security (Martínez *et al.*, 2018b). Therefore, evaluating different fertilization schemes in Chalqueño corn plants will allow us to know which is the best strategy to improve the composition and structure of the soil and thus be able to obtain better grain yields.

MATERIALS AND METHODS

Study site

For field experiments, the total area of the experimental plot was 432.4 m² (18.8 m wide by 23 m long), during the years 2019-2020, within the facilities of the Escuela Superior de Apan, UAEM, Hidalgo, México. At the coordinates 19°65'50" LN and 98°51'88" LW, at 2,488 masl, under temporary conditions. The prevailing climate of the study area is temperate sub-humid, with rains in summer, with an average annual temperature of 14.1°C and 622 mm of average annual precipitation (Cuervo-Parra *et al.*, 2022).

Corn seeds origin

For this research, white creole corn seeds of Chalqueño race were used, defined within the conical group, which includes corn races that are planted in the high parts of central Mexico (Mota *et al.*, 2020b). The seeds were obtained from a local corn producer, located in the municipality of Apan, Hidalgo, Mexico, corresponding to the crop cycle of the year 2018.

Treatments and experimental design

In addition to the ANOVA analysis, factorial design was applied which serves as a test for the influence of certain factors on one or several responses and if any interaction. The experiments as shown in Table 1 are listed in standard order as T1 denotes the experiment when all levels are at their lowest, while T4 denotes the experiment when the factors A and B are at combined, for the response variables plant height, stem diameter, ear length and diameter, ears per plant and grain yield.

Table 1. The 2² Factorial Design for the different fertilization schemes on the rhizosphere.

| Treatments | Factors | |
|------------|---------------------|--------------------|
| | Chemical fertilizer | Organic fertilizer |
| T1 | - | - |
| T2 | + | - |
| T3 | - | + |
| T4 | + | + |

T1 (Control): Without fertilizer input. T2 (Chemical fertilizer): (kg ha⁻¹); N (210); P₂O₅ (84) and K₂O (175), with the annual addition of MgO (10), S (37), Zn (2.5) and B (2); T3 (Organic fertilizer): (vermicompost; kg ha⁻¹); N (39), P₂O₅ (23), K₂O (34), Ca (64), MgO (8.1), S (3.2), Cu (0.05), Zn (0.3), Mn (0.3) and Fe (2.2); T4 (combined treatments):

The same number of materials described for the individual treatments T2, and T3 was used in the specified combination for treatment T4.

Each treatment consisted of seven rows 5 m long with a separation between rows of 0.8 m, which represented an area of 28 m². A total of 30 plants were planted per row, separated by 16.67 cm, with a maximum number of 210 corn plants, which corresponds to a density of 75,000 plants per ha⁻¹. To avoid cross contamination and the edge effect (Romero-Cortes *et al.*, 2022a), a space of 1 m of unseeded soil was left between treatments and repetitions.

The preparation of the plot consisted of a fallow and a cross. The planting and evaluation of the experimental plots were carried out during the months of April-October of the years 2019 and 2020 (SMN, 2022). The

application of the fertilizer for the treatments T2, T3, and T4, was carried out three times with two different concentrations: the first during the sowing of the seeds, the second at 35 days, and the third at 65 days, prior to the start of the male flowering. The applied concentration was 20% during sowing, and 40% during the second and third applications, respectively. On the other hand, the T1 treatment was managed without the contribution of any type of fertilizer throughout the entire crop cycle. All treatments were managed in the same way throughout the 6-month growing cycle. For the control of insects considered pests (*Sitophilus zeamais*, *Helicoverpa armigera*, and *Macrodactylus* sp.), cypermethrin was applied at 85, 95, and 105 days after sowing at a rate of 1 L ha⁻¹ applying 20 mL of product per 20 liters of water by spray baths. Weed control was done manually. The harvest of the ears was carried out once the crop reached its physiological maturity between the first and second week of October of the years 2019 and 2020, respectively. At the end of the crop cycle, the following agronomic characters were recorded: plant height, stem diameter, ear length and diameter (cm), ears per plant and grain yield adjusted to 12% H₂O, using the conversion factor of the harvested area with respect to one hectare, expressed in t ha⁻¹ (Romero-Cortes *et al.*, 2022b).

Statistical analysis

The analyses to calculate the growth and yield variables during the stages of vegetative and maturation development, of the Chalqueño corn plants of the four treatments evaluated, were carried out during the months of April-October, of the years 2019 and 2020. The results were compared using a completely randomized design with three replicates. The results obtained were analyzed using an ANOVA and the Tukey HSD test ($p \leq 0.05$). All statistical analyses of the quantified data were performed using the Statistix 10 software (Analytical Software, 2017).

RESULTS AND DISCUSSION

Plant characteristics (height and stem diameter)

For the corn crop, the macronutrients that determine the productivity and adequate growth of the plants are nitrogen and phosphorous, which is why it is necessary to properly manage these two nutrients to optimize crop productivity (Cardona *et al.*, 2021). In this sense, for the variables of plant height and stem diameter, significant differences were observed between the treatments and years of cultivation evaluated (Table 2). The best results were obtained with the Chalqueño maize plants of the T4 and T2 treatments, with values of 234.2 and 242.9 cm and 209 and 230 cm, for plant height and 2.41 and 2.9 cm and 2.22 and 2.64 cm, for the stem diameter, corresponding to the crop years

2019 and 2020, respectively. In this regard, several studies report that the best plant heights were obtained the corn plants were fertilized with a mixed fertilizer, based on the combination of biofertilizers, compost, and the recommended dose of nitrogen, phosphorous, and potassium (Ahmed *et al.*, 2016; Montejo-Martínez *et al.*, 2018; Romero-Cortes *et al.*, 2022b).

Table 2. Characteristics of the stem of the corn plants (height and diameter).

| Key | Harvest year | Plant height (cm) | Stem diameter (cm) |
|-----|--------------|----------------------------|--------------------------|
| T1 | 2019 | 116.1 ± 11.45 ^d | 1.07 ± 0.14 ^g |
| T2 | 2019 | 209.0 ± 17.42 ^c | 2.22 ± 0.27 ^d |
| T3 | 2019 | 206.6 ± 20.77 ^c | 1.98 ± 0.20 ^e |
| T4 | 2019 | 234.2 ± 5.85 ^a | 2.41 ± 0.11 ^c |
| T1 | 2020 | 131.8 ± 16.05 ^d | 1.49 ± 0.25 ^f |
| T2 | 2020 | 230.0 ± 10.35 ^b | 2.64 ± 0.3 ^b |
| T3 | 2020 | 218.6 ± 9.59 ^b | 2.02 ± 0.25 ^e |
| T4 | 2020 | 242.9 ± 7.47 ^a | 2.9 ± 0.33 ^a |

The means with the same letter within the same column do not differ significantly ($p \leq 0.05$, ANOVA and Tukey's test, equivalent to a simultaneous confidence level of 95%); ± Standard error.

The Chalqueño race is one of the most productive landraces in the High Valleys, with tall plants (Mota *et al.*, 2020a). This corn plant requires proper development and growth, the adequate contribution of solar radiation, as well as temperature, nutrients, and adequate humidity (Endicott *et al.*, 2015). This last factor could have determined the lower growth of the corn plants observed during the crop cycle of the year 2019 compared to the following crop year, which based on the report of the National Meteorological Service for the year 2019 was 438.7 mm (SMN, 2022), which constitutes a low precipitation for the state of Hidalgo. In another work, carried out with the creamy and palomo varieties of Chalqueño maize cultivated under a chemical fertilization scheme in the state of Mexico, plant heights greater than 250 cm were reported (González, 2007). The results were superior to the values obtained in this work with the Chalqueño maize plants of the T2 treatment (209 and 230 cm, respectively) of plant height, during the two years of cultivation, managed under rainfed conditions. In this sense, it has been reported that when irrigation and chemical fertilizer are applied to the Chalqueño maize in different geographical regions of Mexico crop can reach a plant height of between 200 and 350 cm (Carrera-Valtierra *et al.*, 2011; Velázquez, 2013). The values are consistent with the results obtained in the corn plants of the T2, T3 and T4 treatments, during the years 2019 and 2020 (Table 2).

On the other hand, organic matter improves water retention, increases infiltration, and soil aeration, allowing the roots of corn plants to penetrate more easily. In addition, cation exchange is increased, acidity is reduced, and nutrients available in the soil are increased, which promotes the proliferation of microorganisms and increased plant development (Agudo, 2014). The interactions mentioned above could be observed in the maize plants of the T3 and T4 treatments, which obtained heights much higher than those obtained by the plants of the T1 treatment. The vermicompost is a culture medium for microorganisms, which could have influenced a better availability of nutrients with the consequent increase in plant height and therefore the leaf area available for photosynthesis. However, the vermicompost provision of nutrients to the maize plants of the T3 treatment was not at the same level as the minerals available in the chemical fertilizer applied to the plants of the T2 treatment (Table 2). In this sense, in a study where the effect of *Azospirillum* sp. strains plus chemical fertilizer was evaluated, an increase in the formation of root tissue of maize plants of the Conic and Chalqueño races was reported (Rangel-Lucio *et al.*, 2011). The effect of microorganism-chemical fertilizer interaction could be verified in the maize plants of the T4 treatment, which were the ones that obtained the highest plant height and stem diameter. Where the joint interaction of microorganisms, with organic matter and chemical fertilizers resulted in an increase in the stem diameter of maize plants (Zulueta-Rodríguez *et al.*, 2020; Romero-Cortes *et al.*, 2022b).

Ear length and diameter

The Chalqueño race is characterized by having large ears with a high number of rows, high germination vigor, and high seedling emergence (Mota *et al.*, 2020a). The ear length showed significant differences observed between the evaluated treatments and crop years, registering the largest ears in the T4 treatment plants. Obtaining average values of 11.26 and 10.83 cm for the ear length, for the years 2019 and 2020, respectively. For their part, plants of the T2 and T3 treatments, registered average values of 9.57 and 10.44 cm, and 9.87 and 9.94 cm for the ear length, for the years before mentioned. The difference between these two treatments was significant for the 2020 year. Finally, the lowest values showed for the variables of ear length and diameter were in the treatment plants T1 (Table 3).

For other populations of Chalqueño maize, cultivated under irrigated conditions and residual humidity, in two different locations of Mexico, ear lengths of between 12.7 to 17.09 cm and 13.41 to 20.85 cm were reported, respectively (Pérez *et al.*, 2007). For its part, in another study conducted in the state of Mexico, for three Chalqueño maize crops, average values for ear

Table 3. Agronomic variables of Chalqueño maize under different fertilization schemes and cultivation years.

| Key | Harvest year | Ear length (cm) | Ear diameter (cm) | Ears per plant | Yield (t ha ⁻¹) |
|-----|--------------|--------------------------|---------------------------|--------------------------|-----------------------------|
| T1 | 2019 | 7.56 ± 0.5 ^d | 3.4 ± 0.1 ^c | 0.59 ± 0.03 ^e | 1.59 ± 0.12 ^f |
| T2 | 2019 | 9.57 ± 0.4 ^c | 3.87 ± 0.2 ^b | 0.81 ± 0.02 ^c | 4.28 ± 0.19 ^c |
| T3 | 2019 | 9.87 ± 0.08 ^c | 3.97 ± 0.03 ^b | 0.83 ± 0.01 ^c | 3.88 ± 0.11 ^d |
| T4 | 2019 | 11.26 ± 0.5 ^a | 3.95 ± 0.006 ^b | 0.9 ± 0.01 ^b | 5.11 ± 0.05 ^b |
| T1 | 2020 | 7.68 ± 0.2 ^d | 3.2 ± 0.1 ^c | 0.74 ± 0.02 ^d | 2.15 ± 0.38 ^e |
| T2 | 2020 | 10.44 ± 0.3 ^b | 4.03 ± 0.11 ^b | 0.9 ± 0.08 ^b | 5.47 ± 0.22 ^b |
| T3 | 2020 | 9.94 ± 0.06 ^c | 3.97 ± 0.04 ^b | 0.9 ± 0.01 ^b | 4.24 ± 0.29 ^c |
| T4 | 2020 | 10.83 ± 0.4 ^a | 4.37 ± 0.09 ^a | 1.04 ± 0.09 ^a | 6.57 ± 0.95 ^a |

The means with the same letters within the same column do not differ significantly ($p \leq 0.05$, ANOVA and Tukey's test, equivalent to a simultaneous confidence level of 95); \pm Standard error.

length and diameter of 14.5 and 5.1 cm, respectively, are reported (González *et al.*, 2008). On the other hand, Chalqueño maize plants from Miahuatlán, Veracruz, Sierra-Macías *et al.* (2014), reported an ear length of 18.5 cm, with a diameter of 4.9 cm. In this regard, the values reported in this work for the variables of ear length and diameter, from treatments T1 to T4, were lower than the values reported in the works, mainly due to the growing conditions typical of the geographical regions where these studies were carried out and the prevailing abiotic factors in the study region during the years in which the experiment was carried out. In this sense, drought causes considerable reductions in the distribution of rainfall, which causes stress on maize plants, reflected in a reduction in the length and diameter of the ear and the consequent reduction in crop yield (Morgan, 1990; Latiffe, 1993). For the years 2019 and 2020 in the study region, average temperatures between 19.82 and 19.27°C and an average annual rainfall of 438.7 and 501.6 mm were reported, whereas the years with the best environmental conditions for corn cultivation report values average precipitation of between 650 to 655 mm and an average temperature of between 18 to 19°C (SMN, 2022). Therefore, the temperatures and average rainfall recorded for the two years of cultivation were factors that evidently had a negative effect that was reflected in the reduction of the length and diameter of the ear observed in the treatments evaluated in this work.

Another factor that could influence the results observed in some of the evaluated treatments was the deficiency or absence of nutrients in the soil, which interferes with the correct development of a crop, preventing it from completing its life cycle under optimal conditions (Sharma and Kumar, 2017; CIMMYT, 2018). In this regard, in the plants of T1 treatment, it was possible to demonstrate the negative effect that the deficiency and/or absence of nutrients has on the agronomic variables evaluated. Where the deficiency of N and P can have negative effects on the growth and correct development of the ears of maize plants (CIMMYT, 2018). On the other hand, in plants

of the T2 and T3 treatments, although the ear lengths and stem diameter were higher than those obtained in the ears of the T1 treatment, a slight deficiency of these nutrients was observed, with respect to the reported values for the ears of the T4 treatment, during the two years of cultivation. On the other hand, for the ear diameter variable, for the year 2019, there were no significant differences between treatments T2 to T4 and for the year 2020, the treatments T2 and T3 were statistically similar, while the treatment T4 was statistically different. Finally, as expected, the ears of the T1 treatment were the ones that reported the smallest ear diameters.

Ear per plant

For the ears per plant, significant differences were observed between most of the treatments evaluated. The best results were observed during the 2020 crop cycle, for the T4 treatment plants with a value of 1.04 ears per plant. Slightly lower values of 0.9 ears per plant were recorded for the plants of the T2 and T3 treatments for the year 2020 and for the plants of the T4 treatment corresponding to the 2019 crop cycle. On the contrary, plants of the T1 treatment were the ones that registered the lowest values for the two years of cultivation (Table 3).

For Chalqueño blue corn plants, grown under rainfed conditions and a chemical fertilization scheme (120N-60P-30K kg ha⁻¹), a ratio of ear per plant of 0.59 to 0.86 is reported (Arellano *et al.*, 2014). These results are similar to the percentages of 0.81 and 0.83 ears per plant obtained in treatments T2 and T3, during the year 2019. In this regard, periods of atypical rainfall during key stages of the crop can cause the abortion of grains and ears, giving rise to ear percentages below one unit (Romero-Cortes *et al.*, 2022b). In other studies, with Chalqueño maize was reported that they can obtain from 0.9 to 1.1 ears per plant, under very favorable experimental and rainfed conditions (Arellano *et al.*, 2003; Velázquez, 2013). It is evident that the differences observed between the different populations of Chalqueño maize, studied in different geographical

regions of Mexico, are partly due to the genetic information of each biological material, and its adaptation to the biotic and abiotic factors of each locality which in the end is expressed in a higher or lower grain yield.

Grain yield

When analyzing all the treatments evaluated, significant differences ($p \leq 0.05$) were observed between the treatments of the same year and between the years of cultivation, where the best yields corresponded to the treatments of the year 2020 (Table 3). Most likely, due to the increase in precipitation (502.6 mm) and decrease in temperature (19.27°C) reported for the year 2020, compared to the lower values of precipitation (438.7 mm) and higher temperatures (19.82°C) corresponding to the year 2019 (SMN, 2022). In this sense, some conditions like temperatures outside the range of crop adaptation, can have a negative impact on important processes of plants such as photosynthesis, translocation, fertility, successful pollination, and other aspects of metabolism (Lafitte, 1993). Where the crop can spend many hours of the day outside the acceptable limits in order to have an adequate development and therefore obtain a good grain yield. On the other hand, low rainfall during key crop periods, such as flowering and/or grain filling, can cause losses in corn production, reducing crop grain yield (Banco de México, 2021). This could be verified in the lower yields obtained in the four treatments evaluated during the year 2019, which was characterized by having low rainfall and high temperatures (SMN, 2022).

The SIAP (Sistema de Información Agroalimentaria y Pesquera) reports grain yields of 4.3 and 3.8 t ha⁻¹, for the Chalqueño race cultivated in the High Valleys, by irrigation and temporary, respectively (CIMMYT, 2022). In this sense, the results obtained during the two years of cultivation, the T4 treatment was the one that obtained the best grain yields, with average values of 5.11 and 6.57 t ha⁻¹, which surpassed the values above for the same race reported by SIAP, for High Valleys. In this regard, in a study carried out with cotton, rice, sorghum, wheat, and maize in India and China and with potatoes in Bolivia, the best yields were reported when a mixed fertilizer based on the combination of compost and chemical fertilizers was used, instead of individual treatments of said fertilizers (Montaño-Carrasco *et al.*, 2017). Other works reported an evident increase in grain yield, when organic and chemical fertilizers were combined (De Luna-Vega *et al.*, 2016; Solís, 2021), representing an agronomic management alternative aimed at increasing crop yields (Romero-Cortes *et al.*, 2022b). In that sense, the organic matter present in the vermicompost provides a complete and balanced source of nutrients that, together with the chemical fertilizer, favors the growth and yield of corn

plants (Sosa-Rodriguez and García-Vivas, 2018; De Luna-Vega *et al.*, 2016). In northwestern Mexico, grain yields of more than 16 t ha⁻¹ for rainfed and 22.4 t ha⁻¹ for irrigation have been reported, using a cross-fertilization system based on a combination of chemical, organic, and biological fertilizers (Reyes, 2019; Reyes-Figueroa, 2019). In this sense, the results obtained in this work for T4 treatment plants during the two years of cultivation (Table 3), corroborate the increase in grain yield reported by the aforementioned authors.

On the other hand, the T2 treatment plants showed acceptable grain yields, with average values of 4.28 y 5.47 t ha⁻¹, for the years 2019 and 2020. Likewise, for several populations of Chalqueño maize, evaluated in different geographical regions of Mexico, under a chemical and temporary fertilization scheme, grain yields of between 2 and 10.5 t ha⁻¹ were reported (Arellano *et al.*, 2003; Miguel *et al.*, 2004; González, 2007; González *et al.*, 2008; Arellano *et al.*, 2014; López-Morales *et al.*, 2021). When Chalqueño maize plants are managed under an irrigation and residual moisture system in various production environments in Mexico, grain yield values of between 0.71 and 4.1 t ha⁻¹ and 0.87 to 3.39 t ha⁻¹ had been reported, respectively (Pérez *et al.*, 2007).

For his part, the Chalqueño corn plants of the T3 treatment, fertilized with vermicompost, obtained an average grain yield of 3.88 and 4.24 t ha⁻¹ corresponding to the two years of cultivation. In other work, using maize plants of the NB-S variety, the influence of three doses of vermicompost (3, 4, and 5 t ha⁻¹) applied two times (50% at 25 days and 50% at 45 days) were evaluated, reporting slightly higher grain yields of 4.6, 4.58 and 4.5 t ha⁻¹, respectively (Díaz and Montenegro, 2005). Higher yields of 8.88 t ha⁻¹, had been reported in Aguascalientes State, Mexico with white corn plants, which plants were fertilized with 10 t ha⁻¹ of vermicompost (Ramos *et al.*, 2016a). Unlike chemical fertilizers, organic fertilizers such as vermicompost offer plants a supply of slow-release nutrients, through the action of microorganisms (Romero-Figueroa *et al.*, 2015). Increasing the moisture retention of the soil, improving its structure, increasing the nutrient content, and preventing the appearance of diseases in plants, improving the physical-chemical-biological properties of soils (Ramos *et al.*, 2016b; Cardona *et al.*, 2021; Romero-Cortes *et al.*, 2022b). However, the grain yields obtained from vermicompost-based fertilizers were lower than those obtained with a chemical fertilization scheme (De Luna-Vega *et al.*, 2016).

Finally, the lowest grain yields obtained during the study time of cultivation were recorded in the T1 treatment plants. In this sense, had been reported that the soil fertility loss is due to its constant deterioration,

because of the lack of implementation of conservation practices in the plots, thereby progressively decreasing like this the amount of organic matter, the diversity of microorganisms, and increasing erosion of the properties (Solís, 2021). Likewise, it has been seen that an adequate strategy to avoid the erosion of agricultural soils is the application of organic matter, such as compost, vermicompost, or bokashi (Ruiz, 2019; Romero-Cortes *et al.*, 2022b). In the High Valleys region (Estado de México, Hidalgo, Morelos, Puebla, and Tlaxcala), under rainfed conditions, producers obtain yields of between 2 and 3.5 t ha⁻¹ due to root lodging problems, pests, and weeds, mainly (Miguel *et al.*, 2004; CIMMYT, 2022). Conditions that could explain the lowest grain yield obtained in T1 treatment plants during the two consecutive years of cultivation. In this regard, the ability of each crop to take advantage of the rainfall regime, soil fertility, temperature, and agronomic management will considerably influence the maximum yield that it can achieve, being better under conditions of its own ecological niche (Romero-Peñalosa *et al.*, 2002).

The difference in grain yield observed in Chalqueño maize plants during the two years of treatment in the crop in this study could be related to some extent to climate change. About that, for the Tlaxcala state, the potential distribution of four primary maize races (Cacahuacintle, Chalqueño, Cónico, and Elotes cónicos) was modeled with the Maxent algorithm, projected to three specific dates (Hernández *et al.*, 2018). Their results showed that the Chalqueño race could be the most affected by the reduction of potential planting areas, with 7.8, 8.2, and 8.3% for 2020, 2050, and 2080 scenarios, compared to its current distribution area. This is explained because the Chalqueño race is a late maize (it requires more time to pass from its vegetative to reproductive phase), a situation that makes it vulnerable to extreme environmental factors. In this sense, the use of mixed fertilizers, based on vermicompost (source of organic matter and microorganisms) and chemical fertilizer, could help mitigate the unfavorable prognosis reported for this corn race, maintaining adequate conditions for its cultivation, in the High Valley region of Mexico, under temporary conditions.

CONCLUSION

All the treatments of the year 2020 (T1, T2, T3, and T4) showed the best grain yields, while the lowest yields corresponded to the year 2019. The low yield was attributed to the different conditions during the harvest period such as the drought, low precipitation and available moisture in the soil for the plants. The plants where was used T4 treatment with a mixed fertilizer showed tall plants, wide stems, greater ear production, and large ears on average, which was reflected in obtaining better grain yields, during the

two years of cultivation crop. On the other hand, the plants fertilized with chemical fertilizer or organic matter (T2 and T3 treatments), reached heights much higher than the T1 treatment, because they increased the balanced supply of minerals with each fertilizer. Moreover, plants and ears of the treatment T1, evidenced the negative effect of the deficiency and/or absence of nutrients and organic matter in soil, obtaining the lowest grain yields in the two consecutive years of study.

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Compliance with ethical standards. Due to the characteristics of this work does not require the approval by a bioethical committee.

Data availability. The data from this research generated for the evaluation of the growth and yield variables of maize plants are available from the corresponding author (romero@uaeh.edu.mx), upon request.

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