RELATIONS BETWEEN THE MASS OF THE FRUITS, THE NUMBER OF FRUITS PER PLANT AND THE AGRICULTURAL YIELD IN PEPPER, WITH INCREASING SILICON DOSES †

[RELACIONES ENTRE LA MASA DE LOS FRUTOS, EL NÚMERO DE FRUTOS POR PLANTA Y EL RENDIMIENTO AGRÍCOLA EN PIMIENTO, CON DOSIS DE SILICIO CRECIENTES]

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SUMMARY

Background: Statistical relations between the components of agricultural yield and the yield itself after Si treatment as possible non-destructive methods are important for predicting and monitoring the harvest. **Objective:** To measure the relationships between the mass of the fruit, the number of fruits per plant and the agricultural yield in pepper, with increasing silicon doses. **Methodology:** The research was carried out at Quevedo State Technical University, Ecuador in a completely randomized design and three repetitions per treatment. The treatments used were 0, 20, 25 and 30 g potassium silicate plant^{-1}. The variables evaluated were fruit weight, number of fruits per plant and agricultural yield at the time of harvest. Path analysis, multiple and single linear regressions, and nonlinear regressions were performed. **Results:** The path analysis showed a greater direct effect of the number of fruits per plant with and without the presence of silicon. Fruit weight, number of fruits per plant, and agricultural yield increased linearly with increasing silicon dose. **Implications:** The best adjustment of fruit weight both in the presence and absence of silicon when it is related to the yield corresponded to a non-linear model, specifically to a Hill sigmoidal function. **Conclusion:** Through multiple linear regression, it was shown that both yield component variables, i.e. fruit weight and number of fruits per plant, have a greater influence on agricultural yield when fertilized with silicon.
Key words: predictive yield; harvest; potassium silicate; multiple linear-regression.

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RESUMEN

Antecedentes: Las relaciones estadísticas entre los componentes del rendimiento agrícola y el rendimiento mismo como posibles métodos predictivos no destructivos son importantes para predecir y monitorear la cosecha. **Objetivo:** Medir las relaciones entre la masa del fruto, el número de frutos por planta y el rendimiento agrícola en pimiento, con dosis crecientes de silicio. **Metodología:** La investigación se llevó a cabo en la Universidad Técnica Estatal de Quevedo, Ecuador en un diseño completamente al azar y tres repeticiones por tratamiento. Los tratamientos utilizados fueron 0, 20, 25 y 30 g silicato de potasio planta^{-1}. Las variables evaluadas fueron peso de frutos, número de frutos por planta y rendimiento agrícola al momento de la cosecha. Se realizaron análisis de ruta, regresiones lineales simples y múltiples y regresiones no lineales. **Resultados:** El análisis de sendero mostró un mayor efecto directo del número de frutos por planta con y sin presencia de silicio. El peso de los frutos, el número de frutos por planta y el rendimiento agrícola aumentaron linealmente al aumentar la dosis de silicio. **Implicaciones:** El mejor ajuste del peso del fruto tanto en presencia como en ausencia de silicio cuando se relaciona con el rendimiento agrícola correspondió a un modelo no lineal, específicamente a una función sigmoidea de Hill. **Conclusión:** Mediante regresión lineal múltiple, se demostró que ambas variables componentes del rendimiento, es decir, peso del fruto y número de frutos por planta, tienen mayor influencia en el rendimiento agrícola cuando se fertiliza con silicio.

Palabras clave: rendimiento predictivo, cosecha, silicato de potasio, regresión lineal múltiple.

INTRODUCTION

Pepper production (*Capsicum annuum* L., Solanaceae) worldwide is increasing both for domestic consumption and export (Abdelaal *et al*., 2020). This vegetable is grown in more than 40 countries and is the second most consumed in the world after tomato (Hulse-Kemp *et al.*, 2016). Its importance lies in its high contents of vitamin C, carotenoids and flavonoids present in the fruit (Sánchez *et al.*, 2015). In Ecuador it is one of the most cultivated and commercialized crops under greenhouse conditions as well as in the field (Gavilanes-Terán *et al.*, 2017).

At present, to obtain high yields in pepper, excessive use of fertilizers is made (Adom *et al.*, 2024). However, these fertilizers cause damage to the environment, human and animal health, and resistance to phytopathogens (Sabiha-Javied *et al.*, 2023). In addition, they cause soil erosion, salinity and accumulation of heavy metals, air pollution and increases in the greenhouse effect (Li *et al.*, 2022; Wang *et al*., 2022). Therefore, it is necessary to search for alternatives to decrease fertilizers use and that do not cause damage to the environment while increasing yield (Candido *et al.*, 2023).

Silicon is an important element that covers 28% of the lithosphere, having been recently included as an "almost essential" element, according to the International Institute of Plant Nutrition (Abdelaal *et al.*, 2020). Silicon applications can alleviate various types of abiotic stress, such as salinity, drought, and low temperatures (Etesami and Jeong, 2018). In addition, silicon application detoxifies metal ions in plant tissues, enhances the antioxidant defense system, and increases ascorbate and glutathione concentrations, suggesting that silicon can effectively mediate tolerance to heavy metal toxicity (Hasanuzzaman *et al.*, 2017; Emamverdian *et al.*, 2018). Furthermore, the application of silicon enhances stomatal conductance and CO_2 assimilation rate in plants (Yin *et al.*, 2013), stimulates the growth and development of plants and increases crop yield (Bijalwan and Mishra, 2016; Hasan *et al.*, 2016; Bundela *et al.*, 2018).

The objective of this research was to measure the relationships between the mass of the fruit, the number of fruits per plant and the agricultural yield in pepper, with and without the application of silicon.

MATERIALS AND METHODS

Plant material and growth conditions

The field experimental phase was developed in a tunnel-type greenhouse with a semi-transparent polyethylene cover and natural ventilation with side vents at “La Maria” experimental campus belonging to the Quevedo State Technical University (1° 04' 48.6"S, 79° 30' 4.2"W) from March to June 2021. The campus is located at an altitude of 75 m in a humid tropical climate zone, with an average annual temperature of 25.3 °C, average annual rainfall of 1587 mm; 86% relative humidity and 994.4 hours of sunshine per year. The soil presents a flat topography, and loamy-silty texture with an average pH of 5.5 (INAMHI, 2021).

It used a Pepper (*Capsicum annuum* L.) hybrid Quetzal (Seminis seed Company) seeds, which were germinated in 200-cavity polystyrene trays containing a peat moss-perlite growth medium (70/30; *v/v*). At 65 days of age, they were transplanted into 10 L polyethylene pots, with 8 L of growth medium made up of peat moss- perlite in a 1:1 ratio (v/v). Nutrition was supplied through the Steiner nutrient solution (Steiner, 1961) and an automated irrigation system.

The greenhouse condition during the crop cycle were 22 °C temperature and 52% relative humidity. The average maximum conditions were 558 µmol m^{-2} s^{-1} of photosynthetically active radiation, 1,050 W m^{-2} of incident solar radiation (outside the greenhouse), and 738 W m^{-2} inside the greenhouse. The pots were ordered with a separation of 0.90 x 0.35 m, obtaining a total experimental area of 31.5 m^2. Thirty days after transplanting (DAT), the plants were tutored using white agricultural raffia.

Experimental design and treatment application

The experimental design was a completely randomized. Silicon as potassium silicate (Sigma-Aldrich) was used at concentrations of 0, 20, 25, and 30 g L^{-1} per plant, supplied via drench at the base of the stem at transplantation stage. Each treatment consisted of ten plants, each one represented an experimental unit (EU).

Agronomic variables evaluated

At 115 days after transplanting, five EUs of each treatment were considered for evaluation. The variables evaluated were the number of fruits per plant, mean fruit weight (g) with a granatary balance (SPX2202, OHAUS, Inc., NJ, USA) and agricultural yield (kg ha^{-1}).

Statistical analysis

A path analysis or structural equations analysis was carried out, for which agricultural yield was selected as the dependent or response variable and the number of fruits per plant and the mean fruit weight as causal or predictor or independent variables. The path analysis was carried out in two parts: one with the data from the treatment where no silicon was applied (control), so for this analysis the data from the treatment or in which silicon was not applied as fertilizer were excluded, while the other analysis corresponded to the data from the treatments where silicon was applied. The purpose of the path analysis was to establish possible causal explanations in the observed correlations deduced from the value of the correlation coefficient, r (Di Rienzo *et al*., 2019) that are established between the agricultural yield or dependent variable and the two-component variables of agricultural yield or predictive or independent variables mentioned with and without the application of silicon separately.

Different simple linear and non-linear regression models were tested to find the best fit between the different doses of silicon that were used in the experiment as independent variable (x), and agricultural yield, the mean fruit weight and the number of fruits per plant as dependent variables (y). The best fit as a selection criteria corresponded to a simple linear regression since the probability (p) of the model was significant, the adjusted determination coefficients were higher ($R^2_{adj.}$) and the Akaike Information Coefficient (AIC) and Bayesian Information Coefficient (BIC) were lower. The equation of the simple linear regression model is also shown for each dependent variable with the value of the slope (a) and the intercept (b) of the equation y= a+bx. The simple linear regression algorithm used was ordinary least squares.

A multiple linear regression model was used in the absence and the presence of silicon separately for the same variables to find the existence or not of a functional relationship of the multiple linear types when considering the two-component variables of agricultural yield, the number of fruits per plant and the mean fruit weight. The statistics used for the multiple linear regression were p at 95.0% confidence, Mallows's Cp and $R^2_{adj.}$ for both regression variables, the estimated value and the probability (p) of the model of the constant. For the general model of multiple linear regression, p, ($R^2_{adj.}$, AIC and BIC were determined).

A simple classification analysis of variance was performed to determine the presence or not of significant differences between the silicon treatments used concerning the variable average weight of a fruit using Kruskal Walli's test. The multiple comparisons of the treatments were carried out through Conover´s test (1999) for a probability $p \leq 0.05$. All the automated processing of the data in this part was done using the statistical package Infostat version 2019 (Di Rienzo *et al*., 2019).

Finally, a simple non-linear regression analysis was applied between the mean fruit weight and agricultural yield to find out which function, among different simple non-linear regression models, produced the best fit based on R^2 and AIC. The lower and upper confidence intervals (CI) for 95.0% reliability and 1999 permutations were determined for the curve, using the PAST 4.12 software (Hammer *et al.*, 2001).

Before all the statistical analyses, the adjustment to the normal distribution was verified through the modified Shapiro-Wilk test, in which the variable mean fruit weight showed significant values ($p \leq 0.05$), which made it necessary to normalize data using the Accumulate function; the rest of the variables studied did not yield significant values. The other verified premise was the homogeneity of the variances for which the Levene test was applied. With this test, all the variables fulfilled this premise.

RESULTS

Path analysis without and with silicon

The path analysis (Table 1) without added silicon demonstrated the existence of a significant correlation between agricultural yield and the number of fruits per plant. The relationship was indirect with the average weight of a fruit and a lower path coefficient. No correlation was found between agricultural yield and the mean fruit weight in the absence of silicon, and this was more influenced by the mean number of fruits per plant in an indirect way since the value of the path coefficient was higher.

Table 1. Path coefficients between the weight of the fruits, the number of fruits per plant and the agricultural yield in pepper, with or without silicon.

Effect	Via	Coefficient	*p
Without silicon			
NFP	direct	0.72	-
NFP	fruit	0.09	-
total r	-	0.81	0.0145*
Fruit weight	direct	0.22	-
Fruit weight	NFP	0.29	-
total r	-	0.52	0.1911
With silicon			
NFP	direct	2.72	-
NFP	fruit	-1.82	
total r	-	0.90	0.0010*
Fruit weight	direct	-1.85	-
Fruit weight	NFP	2.89	-
Total r	-	0.84	0.0044*

* The direct effect of the number of fruits per plant (NFP) and the weight of fruit on agricultural yield is reflected, and the indirect effects of the weight of a fruit and the number of fruits per plant without the applied silicon and with applied silicon. The significance value for $p < 0.05$.

Silicon applications caused both the number of fruits per plant and the mean fruit weight to correlate with agricultural yield, and the highest path coefficients are directly maintained both for the number of fruits per plant and indirectly for the mean fruit weight, suggesting that between the number of fruits per plant and the mean fruit weight as components of agricultural yield, the number of fruits per plant has a direct and presumably more linear influence concerning the mean fruit weight.

To disclose the best functional relationship between agricultural yield as a response or dependent variable with the number of fruits per plant and the average weight of a fruit as a predictor or independent variable, a multiple linear regression analysis was carried out on the criterion of the existence of the correlations found in the path analysis.

Simple linear regression between silicon dose and agricultural yield, mean fruit weight and number of fruits per plant

As the dose of silicon increased, the agricultural yield, the mean fruit weight, and the number of fruits per plant increased, and it was possible to demonstrate that this increase was linear (Table 2), because the model of the simple linear regression test yielded significance p, a high $R^2_{adj.}$, which in the case of agricultural yield means that 79.0% of variations were due to the three doses of silicon applied, and very similar coefficients of determination among them, but high for mean fruit weight, and the number of fruits per plant.

Multiple linear regression and simple nonlinear regression without and with silicon

Without the presence of silicon in the fertilization, the multiple regression analysis showed (Table 3) that the influence of the variables fruit weight and the number of fruits per plant together do not influence agricultural yield in a linear way as it does not show significance. the model ($p = 0.2316$), and that for this model the weight of the fruit only influences 27.0, for 16.0% of the number of fruits per plant in relation to agricultural yield.

The probability of the model in the presence of silicon in the multiple linear regression analysis showed significance ($p = 0.0015$), which denotes the influence of the variable weight of the fruits and the number of fruits per plant together linearly influencing the agricultural performance, and that between these two independent variables individually, the number of fruits per plant is the variable that influences in a significant linear way ($p = 0.022$), that agricultural performance depends 81.0% on the number of fruits per plant, variable to which the lowest values of Mallows's Cp corresponded.

In general, the best fit to the multiple linear regression model corresponded to the presence of silicon in the fertilization because the probability of the model (p model) was significant, the coefficient of determination (R2adj) was highest (0.85) and the lowest values from the AICc, BIC and Mallows's Cp.

Table 2. Associated statistics of the simple linear regression between the different doses of silicon used.

Variables	p model	$R^2_{adj.}$	AIC	BIC	Equation
Agricultural yield	0.0001	0.79	313.4	316.2	y = 324.9+12324x
Mean fruit weight	0.0001	0.92	170.0	172.5	y = 8.5+345.5x
Number of fruit plant	0.0001	0.93	61.03	63.53	y = 0.36+11.25x

* The independent variable (x) and the dependent variables (y) agricultural average weight of fruit and the number of fruits per plant by the algorithm of ordinary least squares for a probability $p < 0.05$.

The multiple regression analysis (Table 3) in the absence of silicon was not significant because the probability of the multiple linear regression model was not significant. Under silicon fertilization, a change in the linear relationships of the variables occurred, becoming significant for the multiple linear regression model, due to a significantly greater influence of the number of fruits per plant, with a high R^2 that suggests that in these experimental conditions, the variability of agricultural yield is due in 81.0% to the variation in the number of fruits per plant, and between the two predictor variables, which are responsible for 85.0% of the variation.

The AIC, BIC and Mallows's Cp statistics are the ones that are mostly used to find the simple or multiple regression model that best fits. The AIC controls the increase in error each time new terms are included in the model, the corrected AICc adjusts the model in cases where the sample sizes are small. BIC and Mallows's Cp are variants of AIC with the difference that BIC uses Bayesian methods (Bai et al. 2022, Rainsut, 2023).

The sigmoidal function between agricultural yield and the average weight of a plant´s fruit without added silicon (Figure 1A) showed that when the average weight of a fruit is between 347 and 350 g, it does not seem to have a direct influence on the increase in agricultural yield, with a very wide dispersion of the values of agricultural yield by increasing the width of the CIs with a greater magnitude of the lower CI than the upper one. Between 350 and 351 g there is a narrowing of the lower CIs: between 351 and 352 g is where the agricultural yield reaches its highest value, from which it stabilizes with a narrowing of both CIs.

In the absence of silicon (Figure 1B), the value of R^2 of Hill's sigmoidal model (not lineal model) indicated that the weight of the fruits was responsible for 51.0% of the variability of agricultural yield, with 49.0% for other variables not identifed in this research. The non-application of Silicon (Figure 1B) shows a greater stability of the agricultural yield when the values of the average weight of a fruit go from 450 to 580 g and with tighter CIs, from which and in a sigmoidal trend, there is an increase in agricultural yield. Above the mean weight of a fruit of 600 g, there is a widening of the CIs. The presence of silicon in the experiment (Figure 1A) makes a better adjustment of the nonlinear regression model by increasing R^2 to 0.97 and similar AICc compared to the absence of silicon in the results from the simple nonlinear regression model.

Table 3. Regression coefficients and associated statistics of the multiple linear regression for agricultural yield.

Coefficient	Estimated	p	Mallows's Cp	R^2
Without silicon				
Constant	-12036.1	0.4419	-	-
Fruit weight	64.21	0.1738	5.32	0.27
NFP	192.65	0.2629	10,40	0.16
p model		0.2316		
$R^2_{adj.}$ of the model		0.22		
model AICc		163.16		
model BIC		163.95		
With silicon				
Constant	1560.6	0.756	-	-
Fruit weight	-101.4	0.082	3.51	0.71
NFP	3706.4	0.022*	2.59	0.81
p model		0.0015*		
$R^2_{adj.}$ of the model		0.85		
AICc		119.49		
BIC		118.80		

* The dependent variable and the weight of a fruit and the number of fruits per plant as independent variables, without silicon and with the application of silicon. The significance value for $p < 0.05$. NFP=Number of fruits per Plant.

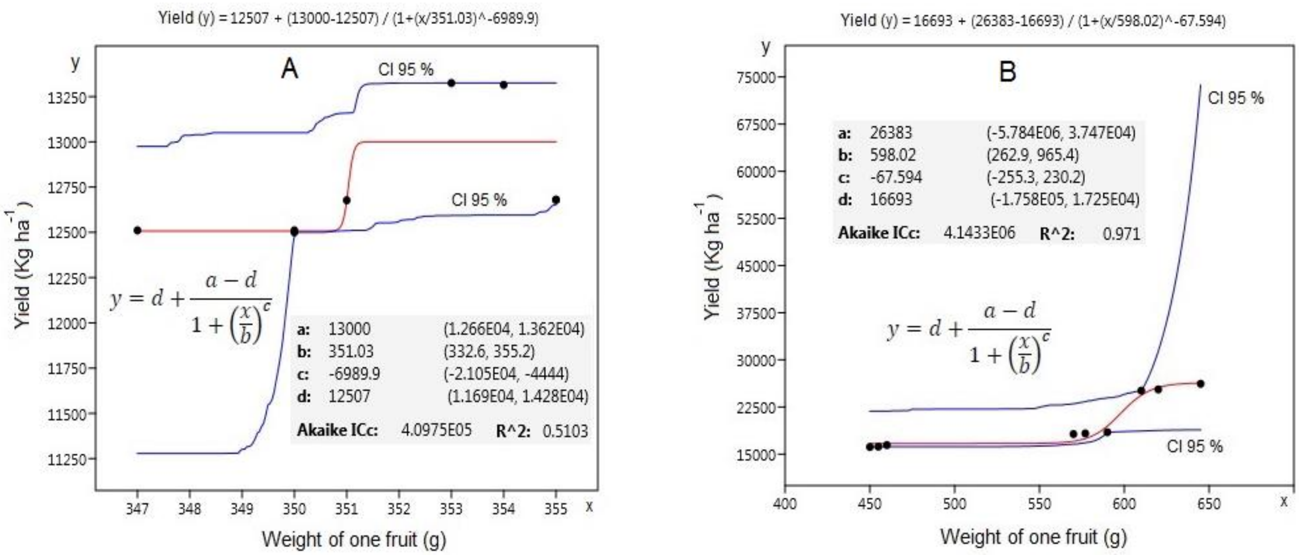

Figure 1. Relationship between the average weight of fruit (x) and the agricultural yield (y, red lines), through a non-linear regression by Hill's sigmoidal function, with the confidence intervals (CI, blue lines) at 95.0% and 1999 permutations, the parameters of the equation (a, b, c and d), the Akaike Information Criterion (AIC) and the coefficient of determination (R^2) without the application of silicon (A) and with the application of silicon (B).

In a sigmoidal model, parameters (a), (b), (c), and (d) have specific meanings and affect the shape of the curve:

(y): Agricultural yield

(x): Weight of a fruit.

(a): It is the upper asymptotic value of the sigmoid curve. It represents the maximum agricultural yield that can be achieved. As the weight of the fruit increases, the agricultural yield approaches this maximum value. This value is higher under the conditions in which silicon was applied, so a higher agricultural yield value can be achieved.

(b): It is a scale parameter and regulates the slope of the curve. Higher values represent a more gradual or less sloping curve; lower values represent a steeper curve. With the application of silicon, the value of this parameter is higher and implies that the sigmoid curve is more gradual, or the existence of a gradual increase in fruit weight with respect to agricultural yield.

(c): Adjust the horizontal position of the curve. Shifts the curve left or right along the x-axis.

(d): Adjust the vertical position of the curve. Moves the curve up or down along the y-axis.

Although the relationship between the mean weight of a fruit and agricultural yield corresponded in this research to a Hill sigmoidal function, mean fruit weight increased with the increase in the dose of applied silicon, with significant differences between the treatments used (Figure 2). The lowest mean fruit weight corresponded to 0 g silicon plant^{-1}, with a mean lower than 400 of 625.0 g, followed by 20 g silicon plant^{-1} –where the mean weight of a fruit did not reach 500 g–, then 25 g silicon plant^{-1}, with a mean fruit weight of 579.0 g and, finally 30 g silicon plant^{-1} with a mean fruit weight of 625.0 g, significantly exceeding the rest of the treatments. The presence of silicon in all the treatments where it was applied was significantly higher than the control treatment, which shows that it stimulates the growth processes and production of dry matter that are used for fruit formation.

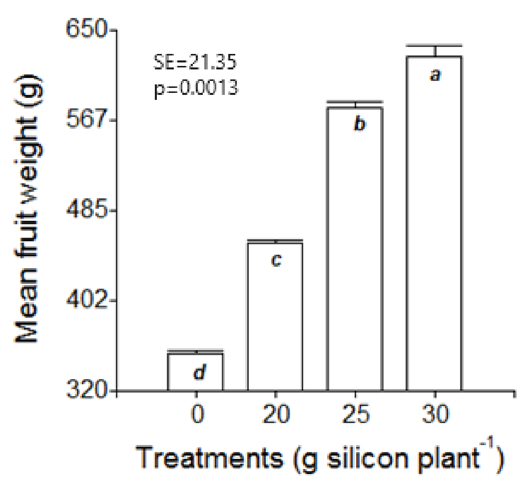

Figure 2. Effect of silicon fertilization treatment on mean fruit weight. Different letters indicate significant differences for $p < 0.05$ with Tukey. SE is the standard error.

DISCUSSION

Path analysis without and with silicon

A path coefficient analysis done on sweet pepper grown under greenhouse conditions in Costa Rica with twelve variables measured in 27 genotypes showed that, similarly to our results, the main direct effect corresponded to the number of fruits per plant, followed by the weight of the fruits (Monge-Perez *et al.*, 2021). Similar results were reported in this crop by Bijalwan and Mishra (2016), and Hasan *et al.* (2016) for the variable number of fruits per plant concerning agricultural yield, while for the weight of the fruits with the greatest positive direct effect on yield, they are similar to what was determined by Dolkar *et al.* (2015) and Bundela *et al.* (2018).

When correlations between different variables of the pepper crop were evaluated, a significant, high, and positive correlation was found between the number of fruits per plant and agricultural yield, both for first-quality fruits and for genotypes with conical and square shapes (Elizondo and Monje, 2019).

Bijalwan and Mishra (2016) when studying 16 pepper genotypes found significant, positive and high genetic and phenotypic correlation coefficients for the yield of fruits per plant with the weight of the fruits and the number of fruits per plant, the difference with our investigation being that the weight of the fruits did not correlate with the agricultural yield in the absence of silicon.

Regarding the use of path analysis in the cultivation of peppers, Mamatha *et al.* (2016), when evaluating different characters in 40 genotypes, found a positive, direct and high effect on the agricultural yield of the number of fruits per plant. Robik *et al.* (2016) demonstrated that the variable number of fruits per plant presented the highest positive direct effect regarding agricultural yield followed by the weight of the fruits per plant, the length of the fruits and the number of primary branches per plant. On the other hand, Pujar *et al.* (2017) reported that the fruiting percentage and fruit weight reached the highest values of the positive direct effect concerning agricultural yield, both for the genetic and phenotypic part.

For the same species studied, other investigations with path analysis in several characters found that the order of the direct positive effects on the agricultural yield corresponded to the dry weight of the fruit, the length and mean diameter of the fruit, and the number of fruits per plant (Shumbulo *et al*., 2017). Bundela *et al.* (2018) concluded for different pepper genotypes that the positive direct effect with the greatest contribution regarding agricultural yield corresponded to the mean weight of the fruits, followed by the length of the fruit, thickness of the fruit pericarp, the number of fruits per plant, diameter of the fruit, the number of seeds per fruit, the days necessary for the first flowering, the number of primary branches, the height of the plant and the days to the collection of the first fruits.

In the same way, Shuweta *et al.* (2018) found through path analysis that the number of fruits per plant, fruit diameter, and the mean fruit weight were characters with the greatest contribution to agricultural yield due to direct and positive effects. These authors consider that these characters can be used as selection indices in pepper breeding programs.

Although to a lesser extent, there are studies on peppers in which negative direct effects have been found, such as the results found by Chakrabarty and Islam (2017), in which the variable days until the first harvest presented a significant effect, but with a negative sign regarding agricultural yield, and they indicate that this character should be considered as negative at the time of selection, to eliminate the undesirable negative indirect effect that it causes, and further enhance the direct effects on agricultural yield.

The importance of using path coefficient or structural equation analysis compared to partial correlation analysis is that the path coefficient separates from the correlation itself the effects that are considered direct from the path coefficients of indirect effects, which are those effects produced by the rest of the variables that make up the analysis (Chakrabarty and Islam, 2017; Pujar *et al.*, 2017; Shumbulo *et al.*, 2017; Shweta *et al.*, 2018 and Monge-Pérez *et al.*, 2021).

Simple linear regression between silicon dose and agricultural yield, mean fruit weight and number of fruits per plant

The variables with the highest adjusted coefficients of determination were those with the lowest values of AIC and BIC. In King Grass (*Pennisetum purpureum*) plant height, stem diameter, plant density, biomass, and dry matter increased with increasing doses of applied silicon (Mejía *et al*., 2019).

Multiple linear regression and simple nonlinear regression without and with silicon

Although the values of AIC and BIC in the presence of silicon were lower than those achieved when silicon was not applied, it can be deduced that they present a better fit to the model but, since p of the multiple linear regression model in the absence of silicon indicated no significance.

Silicon applications showed the number of fruits per plant to have a linear relationship with agricultural yield, a relationship that was not found in the absence of silicon. The variable average weight of a fruit, both with no silicon and with silicon present, did not show a linear relationship with agricultural yield, whose best fit through simple nonlinear regression corresponded to a Hill sigmoid function (Hill, 1910) because among several evaluated simple nonlinear regression functions, it proved to be the one with the value of R^2 and the lowest value of AIC (Figure 1).

The absence of Si in plants can cause a weakening of the structure, reduces the size of organs such as the fruits, delays development, alters the viability of fertilization and produces an increase in susceptibility to environmental stresses (Trejo- Tellez et al., 2020).

On the contrary, the presence of adequate silicon nutrition in plants reduces water loss when it occurs through cuticular transpiration and increases the elasticity of the cell walls in the stage of growth and development as a result of the interaction established between silicon. and certain organic compounds such as pectins and polyphenols, which also causes an improvement in mechanical resistance (Wang *et al*., 2017), arguments that can be the scientific support related to the increase in the variables fruit weight and number of fruits per plant. achieved in this research.

The two components of agricultural yield, i.e. the mean fruit weight and the number of fruits per plant, indicated that when the plant is not fed silicon, these components do not influence agricultural yield in a multiple linear fashion, or that these two variables together do not contribute significantly linearly to agricultural yield. In contrast, when silicon is supplied to the pepper, it seems to stimulate in some way the biochemical and physiological mechanisms responsible to produce fruits per plant due to its linear relationship with agricultural yield, while for the mean fruit weight, the effect of silicon is not linear and fits more to a nonlinear function of Hill’s sigmoidal type.

Fruit development can be evaluated by measuring one or more fruit variables such as fresh and dry weight, diameter, length, and volume. The diameter of the fruit is not considered an adequate measure to evaluate the growth of the fruit because it does not present a linear relationship with either the fresh and dry weight or volume of the fruit (Bollard, 1970; Westwood, 1993).

Most of the fruits follow a growth curve of the sigmoidal type through time (Dey and Brinson, 1984), whose distinctive characteristics are a slow initial development in which cell division occurs, followed by a phase with accelerated exponential growth due to cell expansion that produces an increase in the weight of the fruit and culminates in a final phase in which there is a decline in the growth rate until the time of fruit harvest and is when ripening begins (Coombe, 1976). Many biological variables assume a sigmoidal curve that approximates a nonlinear logistic curve with its four parameters or Hill's equation (Gadagkar *et al.*, 2015). Growth of the pepper fruit follows a simple sigmoid curve (Biles *et al.*, 1973) where the cell division phase occurs in preanthesis and anthesis, and a part in postanthesis, while most of the cell expansion takes place in postanthesis (Munting, 1974).

Unlike the number of fruits per plant, mean fruit weight can be a destructive way of evaluating its relationship with the agricultural yield of the pepper crop. The predictions need to include mean fruit weight in the statistical models that relate the growth of the fruit over time (Maaike, 2010), since in the analysis of the growth of variables that characterize the fruit, they frequently follow a sigmoidal model, as in the case of mean fruit dry weight (Barrera *et al.*, 2008).

These results show that the variable number of fruits per plant must always be taken into account due to its linear relationship with the agricultural yield of the pepper crop when carrying out yield evaluations and could even become an preliminar indicator to predict the possible yield at the time of the transition of the number of flowers and the beginning of the formation of the fruits.

This is a preliminary criterion, because agricultural performance is influenced by many more variables not only of the plant itself, but also from the edaphoclimatic point of view, cases in which other statistical analyzes must be used that integrate all the possible variables and its combination that are include in agricultural yield.

Efficiency can be improved when selecting sweet pepper genotypes to concerning agricultural yield through the selection of the number of fruits per plant (Monge-Perez *et al.*, 2021), although it should be noted that this recommendation is of the phenotypic type, with a great influence of the experimental conditions, where the genetic component can be masked. Therefore, many authors such as Hasan *et al*. (2016) and Roy *et al*. (2019) consider agricultural yield as a phenotypic expression of complex interaction in which agroclimatic and management elements (environment) intervene, in addition to the genetics and physiology of the plant itself (genotype).

Silicon applications in pepper plants produced changes in the morphology and biochemical functions of tissues, such as an increase in plant mass, agricultural yield, and content of chlorophylls, carotenes and lycopenes and, from the biochemical point of view, a marked increase in the activity of the enzyme superoxidase dismutase (Prasad *et al*., 2022), which is an enzyme with antioxidant functions and the formation of a layer of silicic acid found in the epidermis of cells that could be related to the increase in the flexural rigidity of epidermal cells.

The presence of silicon in the mineral nutrition of pepper causes mean fruit fresh weight and the number of fruits per plant as a whole to have a linear influence on agricultural yield through multiple linear regression. Unlike the number of fruits per plant, mean fruit weight is not linearly related to agricultural yield, either in the absence or presence of silicon, but through a nonlinear sigmoidal Hill regression function. The statistical relationships that are established between the number of fruits per plant and mean fruit weight as component variables of agricultural yield constitute predictive methods for monitoring the harvest to be obtained by pepper.

CONCLUSIONS

In conclusion, with the use of path analysis as a statistical tool, it was demonstrated that the number of fruits per plant without and with the presence of silicon in the mineral nutrition of pepper plants var. Quetzal has a direct effect on agricultural yield concerning the average weight of fruit. When increasing the doses of silicon used, the average fresh weight of a fruit, the number of fruits per plant and agricultural yield increase linearly.

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Compliance with ethical standards. Not applicable

Data availability. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request

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Author contribution statement (CRediT). J.J. Reyes-Pérez– Conceptualization, funding acquisition, resources and writing–original draft preparation. **T. Rivas-García–** Conceptualization, project administration, supervision and writing-review & editing. **S. Rodríguez- Rodríguez–** Visualization. **J.A. Torres-Rodríguez–** Data curation. **L.T. Llerena-Ramos–** Investigation. **P. Preciado-Rangel–** Formal analysis. **L.G. Hernández-Montiel–** Writing–original draft preparation. **S.P. Maciel-Torres–** Investigation.

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