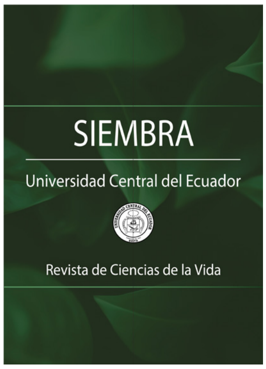
# *Determination of the optimal dose of N, P, and K in the cultivation of Avenger hybrid broccoli (Brassica oleracea italica) in Ecuador*




## *Determinación de la dosis óptima de N, P y K en el cultivo de brócoli hibrido Avenger (Brassica oleracea itálica) en Ecuador*

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**Abstract**

Broccoli is a non-traditional export crop for Ecuador. This study used the response surface methodology to optimize the fertilization of hybrid broccoli, Avenger. The research was conducted at Hacienda Las Mercedes, Cotopaxi province, Ecuador, at 2,913 meters above sea level. We evaluated the response of broccoli to different doses of N-P-K (Nitrogen, Phosphorus, and Potassium), with five levels ranging from 0 to 300 kg ha-1 of N, 0 to 70 kg ha-1 of P, and 0 to 180 kg ha-1 of K, along with one treatment without fertilization. The experimental design was a Central Composite Rotable Design (CCRD) 3K+1 with four replicates. The variables evaluated included plant height, compactness, equatorial diameter, and head yield. The results showed that: i) the greatest plant height (59.90 cm) was obtained with T13 (150 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ P, 90 kg $ha^{-1}$ K); ii) the highest head compactness (1.12 kg $cm^{-2}$) was found with T11 (300 kg $ha^{-1}$ N, 35 kg $ha^{-1}$ P, 90 kg $ha^{-1}$ K); iii) the best equatorial diameter (197.80 mm) and yield (25.25 t $ha^{-1}$) were achieved with T8 (239 kg $ha^{-1}$ N, 56 kg $ha^{-1}$ P, 144 kg $ha^{-1}$ K); and iv) the response surface model suggested an optimal dose of 178 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ P, and 25 kg $ha^{-1}$ K for a yield of 26.5 t $ha^{-1}$. We can conclude that the model adequately fits the crop yield.

**Keywords**: response surface, yield, nitrogen, phosphorus, potassium.

**Resumen**

El brócoli es un cultivo no tradicional de exportación para Ecuador. Este estudio utilizó la metodología de superficie de respuesta para optimizar la fertilización de brócoli híbrido Avenger. La investigación se llevó a cabo en la hacienda Las Mercedes, provincia de Cotopaxi, Ecuador, a una altitud de 2.913 m s. n. m. Se evaluó la respuesta del brócoli a diferentes dosis de N-P-K (nitrógeno, fósforo y potasio) con cinco niveles de dosis crecientes desde 0 a 300 kg $ha^{-1}$ de N, 0 a 70 kg $ha^{-1}$ de P y 0 a 180 kg $ha^{-1}$ de K, y un tratamiento sin fertilización. El diseño experimental fue un compuesto central rotable (DCCR) 3K+1 con cuatro repeticiones. Las variables evaluadas incluyeron la altura de la planta, compactación, diámetro ecuatorial y rendimiento de la pella. Los resultados mostraron que: i) la más grande altura de la planta (59,90 cm) se obtuvo con T13

(150 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ P, 90 kg $ha^{-1}$ K); ii) la mayor compactación de la pella (1,12 kg $cm^{-2}$) se encontró con T11 (300 kg $ha^{-1}$ N, 35 kg $ha^{-1}$ P, 90 kg $ha^{-1}$ K); iii) el mejor diámetro ecuatorial (197,80 mm) y rendimiento (25,25 t $ha^{-1}$) se lograron con T8 (239 kg $ha^{-1}$ N, 56 kg $ha^{-1}$ P, 144 kg $ha^{-1}$ K); y iv) el modelo de superficie de respuesta sugirió una dosis óptima de 178 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ P y 25 kg $ha^{-1}$ K para un rendimiento de 26,5 t $ha^{-1}$. En conclusión, el modelo ajusta de manera aceptable el rendimiento del cultivo.

**Palabras clave:** superficie de respuesta, rendimiento, nitrógeno, fósforo, potasio.

## 1. Introduction

Broccoli (*Brassica oleracea*) has been consolidated as a staple product for non-traditional global exportation (Raya-Montaño et al., 2018). In 2021, global production reached 26 million tons with China and India as top producers (Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO], 2021). In the international agricultural trade, broccoli occupies a prominent position, representing 2 % of the agricultural exportations and taking 3 % of the transitional crop surface in the Highland Region (Ministerio de Agricultura y Ganadería [MAG], 2022a). According to the Survey of Surface and Continuous Agricultural Production [ESPAC] (MAG, 2022b), national yield is about 19.24 t $ha^{-1}$ with 8,725 ha harvested, resulting in a total production of 135,259 t, being Cotopaxi the leader in production (7,697 ha), followed by Chimborazo (465 ha), Tungurahua (445 ha) and Pichincha (119 ha) (Carrillo-Riofrío & Minga-León, 2020).

The growing demand for broccoli in Japan, United States of America and the European Union is due to the preference of light meals, rapid preparation and more nutritious food focused on the health and disease prevention (Moreno et al., 2006; Vélez Duque & Álava Murillo, 2021). Recognized for its high nutritional level and antioxidant and anticancer properties, broccoli plays a fundamental role in future research, specially in the creation of pharmaceuticals and nutraceuticals (Nagraj et al., 2020). This landscape anticipates a promising future for broccoli, not only as healthy food, but as a valuable resource in the search for solutions for human health (Moreno et al., 2006; Vélez Duque & Álava Murillo, 2021).

The optimization of the yield and quality of broccoli is limited by an adequate provision of mineral nutrients (Yildirim et al., 2011). The fertilization is fundamental in production representing between 20 % to 30 % of the costs. However, the excessive use of inorganic fertilizers and salinity problems pose significant challenges for soil fertility, affecting agricultural production and generating negative environmental and health impacts (Carrillo-Riofrío & Minga-León, 2020; Jiménez Villalva & Osorio Bautista, 2019; Mejía Sánchez, 2022). Therefore, it is crucial to find the balance between the dose and the cost of fertilizers to guarantee an adequate nutrition without compromise economic viability of the sector, which can be reached by using more precise fertilization techniques, adapted to the specific needs and local conditions (Román Llamuca, 2022).

In the context of fertilization, nitrogen is identified as the limiting factor in yield production, with recommended doses of 150 and 320 kg $ha^{-1}$ (Cartagena Ayala, 2014; Pantoja, 2006; Puenayan et al., 2008; Román Llamuca, 2022). The application of phosphorous, in quantities from 100 to 200 kg $ha^{-1}$, is essential to avoid the appearance of purple stains in older leaves (Pantoja, 2006; Puenayan et al., 2008; Román Llamuca, 2022). Moreover, potassium, administered in doses of 100 to 300 kg $ha^{-1}$, increases the photosynthetic activity and improves the quality of the crown (Reyes Matamoros et al., 2001; Vidal-Martínez et al., 2006).

The objective of this research is to determine the optimal dose of fertilization, using response surface methodology, adjusted to the specific requirements of broccoli crops to provide an effective, efficient and sustainable recommendation for fertilization.

## 2. Materials and Methods

The research was carried out in field conditions at the Las Mercedes Farm located at the Joseguango Bajo parish, Latacunga canton, Cotopaxi province. This place is located at 2 913 m a.s.l with geographical coordinates of South latitude 00° 48’ 51” and west longitude 78° 36’ 25”.

The soil of the experimental area had a sandy loam texture with 27.5 mg $kg^{-1}$ content of $N\text{-}NO_3$, 1.8 mg $kg^{-1}$ of P, 73.5 mg $kg^{-1}$ of K, 4.7 % of organic matter and pH of 7.2. Broccoli seedlings (*Brassica oleracea* var.), Avenger hybrid, were used in a vegetative state of three leaves (20 days) and size between 5 to 8 cm. The transplant was done with 0.8 m of distance between grooves, and 0.25 m of distance between plants, which resulted in a population density of 52 000 plants ha$^{-1}$. Each experimental unit had a surface of 46.65 m$^2$ (4.8 m wide by 7.92 m long) with 6 grooves.

The study factors were nitrogen [N], phosphorous [P] and potassium [K] applied in five different levels. The doses varied from 0 to 300 kg ha$^{-1}$ for N, from 0 to 70 kg ha$^{-1}$ for P, and from 0 to 180 kg ha$^{-1}$ for K (Table 1).

**Table 1.** Levels of macroelements (N, P and K) in a Central Composite Rotable Design [CCRD].

| Levels | Codified levels | | | Real levels (kg ha-1) | | |
|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | N | P | K |
| **1** | - α | α | - α | 0 | 0 | 0 |
| **2** | - 1 | 1 | - 1 | 61 | 14 | 36 |
| **3** | 0 | 0 | 0 | 150 | 35 | 90 |
| **4** | 1 | 1 | 1 | 239 | 56 | 144 |
| **5** | α | α | α | 300 | 70 | 180 |

α = 1.68.

Sixteen treatments were obtained from the combination of different levels of N, P and K. These treatments were designed using a Central Composite Rotable Design [CCRD] of the form 3K+1, where "K" represents the number of factors. Each treatment was replicated four times (Table 2).

**Table 2.** Treatments to determine the optimal nutritional balance of a Central Composite Rotatable Design [CCRD].

| Treatments | Codified levels | | | Real levels(kg ha$^{-1)}$ | | |
|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | N | P | K |
| **T1** | -1 | -1 | -1 | 61 | 14 | 36 |
| **T2** | -1 | -1 | 1 | 61 | 14 | 144 |
| **T3** | -1 | 1 | -1 | 61 | 56 | 36 |
| **T4** | -1 | 1 | 1 | 61 | 56 | 144 |
| **T5** | 1 | -1 | -1 | 239 | 14 | 36 |
| **T6** | 1 | -1 | 1 | 239 | 14 | 144 |
| **T7** | 1 | 1 | -1 | 239 | 56 | 36 |
| **T8** | 1 | 1 | 1 | 239 | 56 | 144 |
| **T9*** | 0 | 0 | 0 | 150 | 35 | 90 |
| **T10** | -1.68 | 0 | 0 | 0 | 35 | 90 |
| **T11** | 1.68 | 0 | 0 | 300 | 35 | 90 |
| **T12** | 0 | -1.68 | 0 | 150 | 0 | 90 |
| **T13** | 0 | 1.68 | 0 | 150 | 70 | 90 |
| **T14** | 0 | 0 | -1.68 | 150 | 35 | 0 |
| **T15** | 0 | 0 | 1.68 | 150 | 35 | 180 |
| **T16**** | 0 | 0 | 0 | 0 | 0 | 0 |

* Farmer witness: Fertilization at Las Mercedes farm.
** Absolute witness: No fertilization.

Two control treatments were included in the study: *) the farmer witness or control, which represents the fertilization regime used by the Las Mercedes Farm, and **) the absolute control, which represents the total absence of fertilizer application.

Chemical fertilization was applied in three stages. The first was done at the moment of transplant, applying 33 % of N, 100 % of P and 50 % of K. The second stage was carried out at 30 days after transplantion [dat], applying an extra 33 % of N and the 50% of K remaining. The third and last stage took place at 51 days after transplantation, applying 33 % of remaining nitrogen.

The sources of fertilizers used were urea advance (46 % N), triple superphosphate (46 % $P_2O_5$), muriate of potassium (60 % $K_2O$), magnesium sulphate (27 % MgO, 20 % S) and calcimed (30 % CaO, 17 % S). The application was manual.

A Central Composite Rotable Design [CCRD] of the form 3K+1, with four repetitions to evaluate the broccoli answer to different doses of N, P and K was used. This design allowed the analysis of the interactions between factors and the adjustment of a model of response surface that describe the relationship between the fertilizer dose and the answer variables evaluated.

The evaluated variables included:

i) Plant height: measured in the phenological stage V3 (30 dat), V10 (45 dat), VT (60 dat), R1 (75 dat) and R3 (90 dat) from the base of the stem until the main apex with a ruler, expressed in centimeters. The logistic model was used to describe the plant height in function of time, equations [1, 2 and 3] (Alonso Báez et al., 2003).

$$W(t) = \frac{\alpha}{1 + \beta\, e^{-\gamma t}} \tag{1}$$

$$W = \frac{\alpha}{2} \tag{2}$$

$$t = \frac{In\, \beta}{\gamma} \tag{3}$$

where:
*W(t)* = Size over time (*t*).
α = Growth limit value.
β = It does not have biological significance and occurs only at the initial time (*t* = 0).
ɣ = Constant rate that determines the curve amplitude.

ii) Crown compaction: Evaluated in the phenological stage R3 (90 dat) with a pocket penetrometer, expressed in kg $cm^{-2}$.
iii) Equatorial diameter of the crown: measured in the phenological stage R3 (90 dat) using a gauge Vernier and expressed in millimetres.
iv) Crown performance: evaluated at the moment of manual harvest and expressed in t $ha^{-1}$.

The data analysis was done using analysis of variance [ANOVA] to determine significant differences among treatments. For the significant effects, Tukey test at 5 % was used.

Moreover, the surface response model was adjusted for the performance response, using techniques of multiple regression (equation 4). This model allowed the identification of optimal doses of N, P and K to maximize broccoli yield (Gutiérrez Pulido & Vara, 2008).

$$y = \beta_0 + \beta_1 N + \beta_2 P + \beta_3 K + \beta_4 NN + \beta_5 PP + \beta_6 KK + \beta_7 NP + \beta_8 NK + \beta_9 PK + e \tag{4}$$

where:
*y* = Desirable characteristic we want to estimate in function of N, P and K.
$\beta_0$ = Ordinated at the corresponding origin to the estimation of and when N=P=K=0.
$\beta_1, \beta_2, \beta_3$ = Lineal effects.
$\beta_4, \beta_5, \beta_6$ = Quadratic effects.
$\beta_7, \beta_8, \beta_9$ = Double interaction.
*e* = Experimental error.

## 3. Results and Discussion

Plant height showed significant differences (α = 0.01) at 60 days after transplantion (dat), 75 dat (α = 0.05), and non-significant (α > 0.05) at 30, 45 and 90 dat. The coefficients of variation oscillated between 4 % and 13 %, showing an adequate confidence in the data obtained (Table 3).

**Table 3.** Analysis of variation for plant height.

| Source of variation | Degrees of freedom | Medium Square | | | | |
|---|---|---|---|---|---|---|
| | | 30 dat | 45 dat | 60 dat | 75 dat | 90 dat |
| **Total** | 63 | | | | | |
| **Treatments** | 15 | 2.17 ns | 22.58 ns | 34.92 ** | 16.68 * | 18.45 ns |
| **Repetition** | 3 | 2.16 ns | 68.89 ** | 44.37 * | 5.96 ns | 10.55 ns |
| **Error** | 45 | 1.69 | 12.28 | 13.68 | 5.86 | 7.58 |
| **CV (%)** | | 9.52 | 13.60 | 7.87 | 4.34 | 4.76 |
| **Average (cm)** | | 13.65 | 25.75 | 47.01 | 55.66 | 57.80 |

** = significant difference (p value < 0.01); * = significant difference (p value < 0.05); ns = not significant; ddt = days after transplantation.

Tukey test at 5 % for plant height at 75 dat presented two ranges: with T13 (150 kg ha$^{-1}$ N, 70 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) reaching 58.32 cm and T16 (0 kg ha$^{-1}$ N, 0 kg ha$^{-1}$ P, 0 kg ha$^{-1}$ K) with 51.62 cm. At 90 dat, T13 showed the highest plant with 59.90 cm (Table 4).

**Table 4.** Tukey test at 5 % for plant height.

| Treatments | Plant height (cm)* | | | | | |
|---|---|---|---|---|---|---|
| | 30 dat | 45 dat | 60 dat | 75 dat | | 90 dat |
| **T1** | 14.50 | 25.57 | 45.12 | 55.30 | ab | 57.65 |
| **T2** | 12.82 | 26.12 | 42.95 | 52.40 | ab | 54.30 |
| **T3** | 13.97 | 28.50 | 50.70 | 55.82 | ab | 58.87 |
| **T4** | 14.20 | 26.87 | 49.82 | 52.72 | ab | 54.97 |
| **T5** | 13.87 | 26.62 | 45.15 | 56.07 | ab | 59.17 |
| **T6** | 13.07 | 26.32 | 45.10 | 56.55 | ab | 59.32 |
| **T7** | 14.15 | 29.80 | 49.42 | 57.30 | ab | 60.30 |
| **T8** | 13.90 | 29.25 | 49.65 | 56.65 | ab | 58.85 |
| **T9** | 13.90 | 25.45 | 48.05 | 57.17 | ab | 59.42 |
| **T10** | 13.65 | 25.95 | 49.15 | 55.60 | ab | 57.00 |
| **T11** | 13.77 | 23.82 | 45.87 | 56.37 | ab | 57.95 |
| **T12** | 12.95 | 23.65 | 46.67 | 57.95 | a | 59.10 |
| **T13** | 14.85 | 23.27 | 50.37 | 58.32 | a | 59.90 |
| **T14** | 14.17 | 26.92 | 49.47 | 57.22 | ab | 59.12 |
| **T15** | 12.37 | 22.80 | 43.07 | 53.50 | ab | 55.55 |
| **T16** | 12.32 | 21.12 | 41.57 | 51.62 | b | 53.32 |

* Values with the same letter do not show significant statistical differences according to Tukey's test with a significance level of p < 0.05.

The parameters of the logistic model for the plant height showed that T13 (150 kg ha$^{-1}$ N, 70 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) presented the highest values, while T16 (0 kg ha$^{-1}$ N, 0 kg ha$^{-1}$ P, 0 kg ha$^{-1}$ K) the lowest values, and T9 (150 kg ha$^{-1}$ N, 35 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) positioned between the two treatments (Table 5).

In this context and for plant height, the relatively small variations were close and suggested that, in proportional terms, they got increased rapidly in all treatments. This happened because of experimental conditions and characteristics of each treatment. Moreover, the determination coefficient ($R^2$) is equally high in all treatments (0.99), which indicated that the logistic model adjusted well.

**Table 5.** Parameters of the log-normal function for plant height.

| **Treatments** | **Parameters** | | | | | |
|---|---|---|---|---|---|---|
| | α | β | ɣ | **$R^2$** | **w** | **t** |
| **T1** | 60.72 | 38.86 | 0.07 | 0.99 | 30.36 | 47.29 |
| **T2** | 56.49 | 42.84 | 0.08 | 0.99 | 28.25 | 46.11 |
| **T3** | 59.97 | 61.60 | 0.09 | 0.99 | 29.99 | 44.50 |
| **T4** | 56.28 | 64.44 | 0.09 | 0.99 | 28.14 | 43.62 |
| **T5** | 62.07 | 39.51 | 0.07 | 0.99 | 31.04 | 47.69 |
| **T6** | 62.15 | 45.52 | 0.07 | 0.99 | 31.08 | 47.97 |
| **T7** | 61.73 | 48.70 | 0.08 | 0.99 | 30.87 | 44.97 |
| **T8** | 60.29 | 56.06 | 0.09 | 0.99 | 30.15 | 44.54 |
| **T9** | 61.96 | 55.02 | 0.08 | 0.99 | 30.98 | 47.15 |
| **T10** | 59.00 | 67.20 | 0.09 | 0.99 | 29.50 | 45.44 |
| **T11** | 61.13 | 52.76 | 0.08 | 0.99 | 30.57 | 48.07 |
| **T12** | 62.20 | 67.64 | 0.08 | 0.99 | 31.10 | 48.50 |
| **T13** | 62.78 | 68.28 | 0.08 | 0.99 | 31.39 | 47.51 |
| **T14** | 61.26 | 56.78 | 0.08 | 0.99 | 30.63 | 45.85 |
| **T15** | 58.41 | 54.89 | 0.08 | 0.99 | 29.21 | 48.49 |
| **T16** | 56.34 | 55.28 | 0.08 | 0.99 | 28.17 | 48.75 |

α = growth limit, β = has no biological significance and occurs only at the initial time when t = 0 and ɣ = constant rate that determines the amplitude of the curve; $R^2$ = coefficient of determination; w = size over time; t = maximum growth rate.

In this context and for plant height, the relatively small variations were close and suggested that, in proportional terms, they got increased rapidly in all treatments. This happened because of experimental conditions and characteristics of each treatment. Moreover, the determination coefficient ($R^2$) is equally high in all treatments (0.99), which indicated that the logistic model adjusted well.

One of the characteristics that the fertilizer dose presented in T13 (150 kg ha$^{-1}$ N, 70 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) and compared to Zamora (2016), who applied doses of 220 kg ha$^{-1}$ N, 40 kg ha$^{-1}$ P, 0 kg ha$^{-1}$ K, significantly influenced on the vegetative growth, including height. The high content of nitrogen in the broccoli crop is essential for the development of green parts, such as leaves, and stems because it is a fundamental nutrient for the metabolism of proteins and chlorophyll promoting vigorous and healthy growth. Even though an adequate supply of nitrogen promotes growth, an excess can led to a disproportional development of the vegetative parts at the expense of flowering and fructification (Mainardi Fazio, 2017).

The analysis through the logistic model reveled the presence of three distinct phases in the evaluated treatments. An initial phase was identified until the 20 dat, followed by an exponential growth phase that covered from the 20 to the 70 dat. Finally, a stabilization phase or plateau between 70 and 90 dat (Figure 1).

During a study done by Bacarreza Manrique (2018) two broccoli variables, maximum heights of 67.88 cm and 60.94 cm, were registered for Monte Cristo and Green Storm, respectively. This author highlighted that maximum plant height was affected not only by soil fertilization, but also by genetic and environmental factors. The observed differences can be explained by the specific conditions of the crop and the genetic characteristics of varieties, as well as by plant competition and the density of sowing that affects growth. The amount of light available and the temperatures also influence significantly in the optimal development of the plants. In addition, it was observed that lower temperatures at night could favor growth due to a reduction in the respiration rate.

The quality of the broccoli crown was evaluated with compaction, where the analysis of variance did not indicate significant statistically differences among studied treatments with a coefficient of variance [CV] of 14.94 %, which indicated a moderate dispersion in the data (Table 6). The treatment T11 (300 kg ha$^{-1}$ N, 35 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) showed the highest compaction, reaching 1.12 kg cm$^{-2}$, while treatment T5 (239 kg ha$^{-1}$ N, 14 kg ha$^{-1}$ P, 36 kg ha$^{-1}$ K) showed the lowest compaction with 0.82 kg cm$^{-2}$ (Table 7). These results suggested that exist a low variability in terms of density, size and weight, indicating uniform compaction. This attribute is crucial in numerous processes of production and applications, significantly contributing to improve the quality of the final product (Heather & Sieczka, 1991).

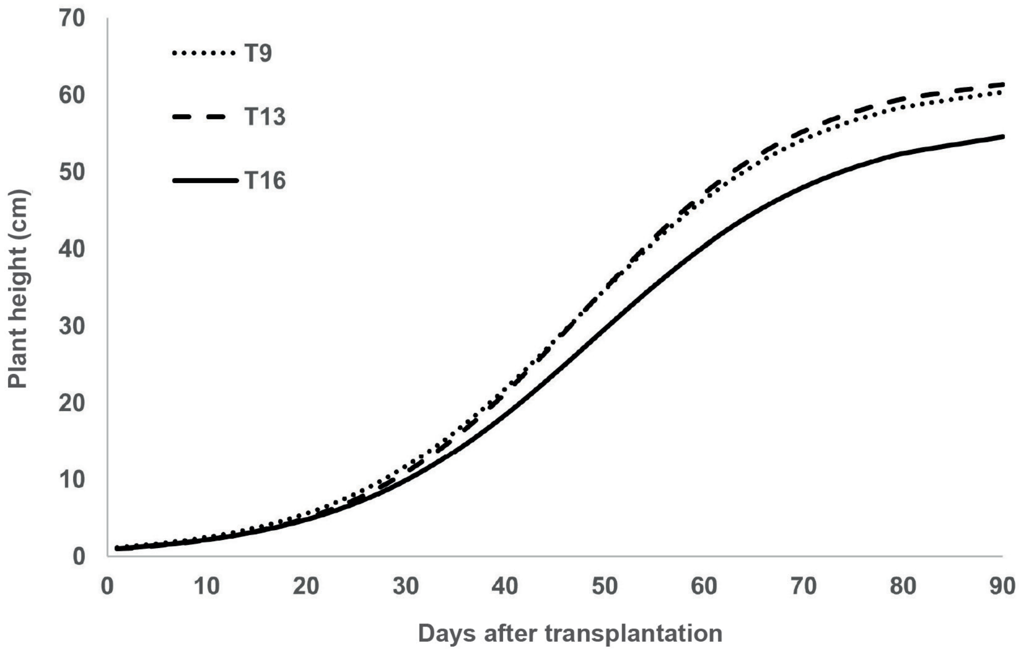


**Figure 1.** Effect of treatments on plant height (T9, T13 and T16).

**Table 6.** Response optimization for broccoli yield. Analysis of Variance for compaction, equatorial diameter, and broccoli crown yield.

| Sources of variation | Degrees of Freedom | Medium Square | | |
|---|---|---|---|---|
| | | Compaction | Diameter | Performance |
| Total | 63 | | | |
| Treatments | 15 | 0.02 ns | 1171.57 ** | 28.85 ** |
| Repetition | 3 | 0.08 * | 1231.06 ** | 83.37 ** |
| Error | 45 | 0.02 | 176.71 | 4.47 |
| **CV (%)** | | 14.94 | 8.11 | 9.68 |
| **Average** | | 0.94 | 163.73 | 21.85 |

** = significant difference (P value < 0.01); * = significant difference (P value < 0.05); and ns = not significant.

Moreover, the equatorial diameter of the crowns was evaluated finding a high statistical significance ($\alpha = 0.01$) among the studied treatments with a CV of 8.11 % that suggests data reliability (Table 6). Through a Tukey test at 5 %, four significant groups were identified. The treatment T8 (239 kg ha$^{-1}$ N, 56 kg ha$^{-1}$ P, 144 kg ha$^{-1}$ K) showed the highest diameter with 197.80 mm, while treatment T12 (150 kg ha$^{-1}$ N, 0 kg ha$^{-1}$ P, 90 kg ha$^{-1}$ K) presented the lowest diameter with 142.87 mm (Table 7).

These responses are consistent with previous studies such as Cuatin Revelo (1998) and Puenayan et al. (2008), who reported diameters that vary between 88.2 mm and 149.2 mm. Lazcano-Ferrat (2006) recorded diameters oscilating between 80 mm and 200 mm, while Hussain et al. (2012) recorded diameters from 91.5 mm until 150.2 mm, which is statistically consistent with those obtained during the present study with doses

of 120 kg ha$^{-1}$ N and 60 kg ha$^{-1}$ N, respectively.
Finally, the analysis of variance for the performance of the broccoli crowns revealed significantly differences ($\alpha = 0.01$) with a coefficient of variation of 9.68 % and an average yield of 21.85 t ha$^{-1}$ (Table 6).

**Table 7.** Tukey test at 5 % for compaction, equatorial diameter, and yield.

| Treatments | Compaction (kg cm$^{-2}$) | Diameter (mm) | | Performance (t ha$^{-1}$) | |
|---|---|---|---|---|---|
| **T1** | 0.91 | 150.72 | cd | 20.83 | abcde |
| **T2** | 0.95 | 145.65 | cd | 19.01 | cde |
| **T3** | 0.99 | 186.12 | ab | 24.11 | abc |
| **T4** | 0.99 | 147.70 | cd | 20.01 | abcde |
| **T5** | 0.82 | 152.77 | bcd | 19.52 | bcde |
| **T6** | 0.99 | 168.25 | abcd | 21.15 | abcde |
| **T7** | 0.89 | 170.90 | abcd | 24.74 | ab |
| **T8** | 0.85 | 197.80 | a | 25.25 | a |
| **T9** | 0.90 | 166.90 | abcd | 23.73 | abc |
| **T10** | 0.96 | 153.05 | bcd | 17.95 | de |
| **T11** | 1.12 | 188.72 | a | 23.29 | abcd |
| **T12** | 0.96 | 142.87 | d | 22.24 | abcd |
| **T13** | 0.97 | 173.97 | abc | 24.39 | abc |
| **T14** | 0.99 | 171.25 | abcd | 24.72 | ab |
| **T15** | 1.07 | 167.25 | abcd | 22.15 | abcd |
| **T16** | 0.91 | 142.87 | cd | 16.45 | e |

* Values with the same letter do not show significant statistical differences according to Tukey's test with a significance level of $p < 0.05$.

The Tukey test at 5 % identified five ranges of performance. The treatment T8 (239 kg ha$^{-1}$ N, 56 kg ha$^{-1}$ P, 144 kg ha$^{-1}$ K) got the highest yield with 25.25 t ha$^{-1}$, while the treatment T16 (0 kg ha$^{-1}$ N, 0 kg ha$^{-1}$ P, 0 kg ha$^{-1}$ K) showed the lowest yield with 16.45 t ha$^{-1}$ (Table 7). The correlation between the variables plant height, compaction, equatorial diameter and yield of the crown determined a high statistical correlation between the equatorial diameter of the crown and yield ($\alpha = 0.01$) but not for the correlation between the compaction of the crown and the equatorial diameter, and neither for the plant height and crown compaction. Overall, these data highlight the importance of height in relationship with the diameter and broccoli yield, while the compaction of crown seems to have a limited influence in these variables (Table 8).

**Table 8.** Pearson correlation matrix for height, compaction, equatorial diameter of the head, and broccoli yield.

| | Height | Compaction | Diameter | Yield |
|---|---|---|---|---|
| **Height** | 1 | | | |
| **Compaction** | 0.1422<br>0.2621 | 1 | | |
| **Diameter** | 0.2993<br>0.0163 | -0.004<br>0.9707 | 1 | |
| **Yield** | 0.3075<br>0.0134 | 0.0731<br>0.5658 | 0.5714<br>0.0001 | 1 |

The analysis of variance for the response surface model showed that the lineal effects of N, P and K are significant ($\alpha = 0.01$) in broccoli yield, while the quadratic interactions did not show significance. This suggests that the individual levels of N and P have a considerable impact in the performance but the combinations between these nutrients do not present a significant synergetic effect. The coefficient of determination ($R^2$) of the model was 0.45, showing that the model explains 45 % of the variability in broccoli yield, which is considered to be moderately acceptable (Table 9).

**Table 9.** Analysis of variance of the multiple regression for broccoli yield.

| Source of variation | Degrees of Freedom | Medium Square | |
|---|---|---|---|
| Lineal | 3 | 63.76 | ** |
| N | 1 | 78.89 | ** |
| P | 1 | 94.53 | ** |
| K | 1 | 17.16 | * |
| Quadratic | 3 | 27.08 | ns |
| NN | 1 | 80.25 | ** |
| PP | 1 | 9.87 | ns |
| KK | 1 | 8.32 | ns |
| Interaction of 2 factors | 3 | 16.02 | ns |
| NP | 1 | 9.84 | ns |
| NK | 1 | 29.20 | ns |
| PK | 1 | 10.17 | ns |
| Error | 54 | 8.93 | |
| Lack of adjustment | 6 | 5.13 | ns |
| Error | 48 | 9.40 | |
| Total | 63 | | |
| **CV (%)** | | 13.67 | |
| **$R^2$** | | 0.45 | |

*** = significant difference (P value < 0.01); * = significant difference (P value < 0.05); and ns = not significant.*

In the analysis of the surface answer model for broccoli performance, the independent term showed a notably statistical significance ($\alpha = 0.01$), with an estimated of 16.76. This suggests the existence of a significant contribution towards the broccoli performance without considering the specific aspects of the nutrients N, P and K. Moreover, the effects of the nutrients N and P were observed, as well as the quadratic interactions of NN. The positive estimator for N showed that an increase in content of N is associated with an increase in performance. Similarly, the estimators for P and the quadratic effect of NN suggested positive increments in the yield. On the other hand, the no significant estimators for K and the rest of interactions (PP, KK, NP, NK, PK) showed that these factors do not have significance in the yield (Table 10).

The polynomial model that explains the effect of fertilization with N, P and K in broccoli yield is $Y = 16.766822 + 0.041978\ N + 0.145246\ P + 0.007657\ K - 0.000184\ NN - 0.001184\ PP - 0.000164\ KK + 0.000279\ NP + 0.000187\ NK - 0.000468\ PK$.

The main effects of the levels of N, P and K showed different patterns: for N, a positive quadratic effect was observed; for P, yield increment is lower, and for K, a negative quadratic effect was presented (Figure 2).

At the effects for the interactions N*P, it can be appreciated that with a fixed value of 0 kg ha$^{-1}$, P is lower. It is the opposite for the other interactions such as N*K and P*K (Figure 3). The effects of the interaction N*P showed that with a fixed value of 0 kg ha$^{-1}$ for P, the yield is the lowest. In contrast, the interactions N*K and P*K presented a different behavior showing higher yield.

**Table 10.** Regression parameters for broccoli yield.

| Parameter | Degrees of Freedom | Estimator | |
|---|---|---|---|
| Independent Term | 1 | 16.766822 | ** |
| N | 1 | 0.041978 | * |
| P | 1 | 0.145246 | * |
| K | 1 | 0.007657 | ns |
| NN | 1 | -0.000184 | ** |
| PP | 1 | -0.001184 | ns |
| KK | 1 | -0.000164 | ns |
| NP | 1 | 0.000279 | ns |
| NK | 1 | 0.000187 | ns |
| PK | 1 | -0.000468 | ns |

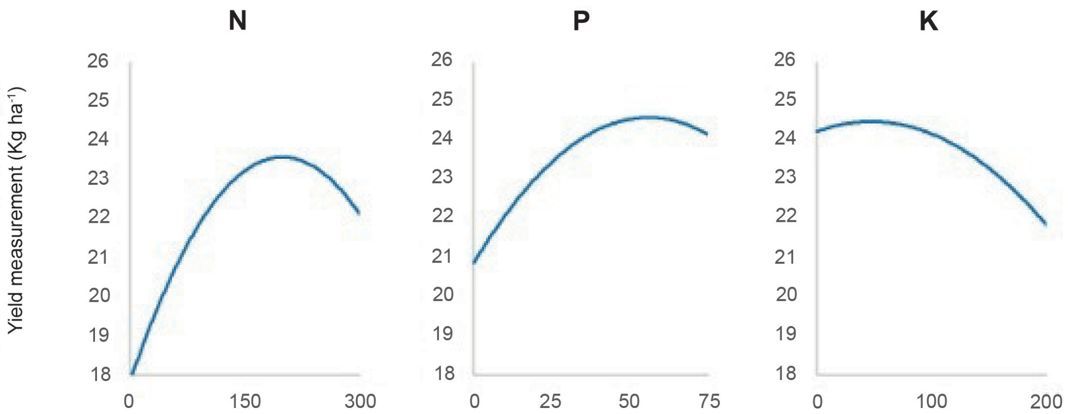


**Figure 2.** Main effects for broccoli yield.

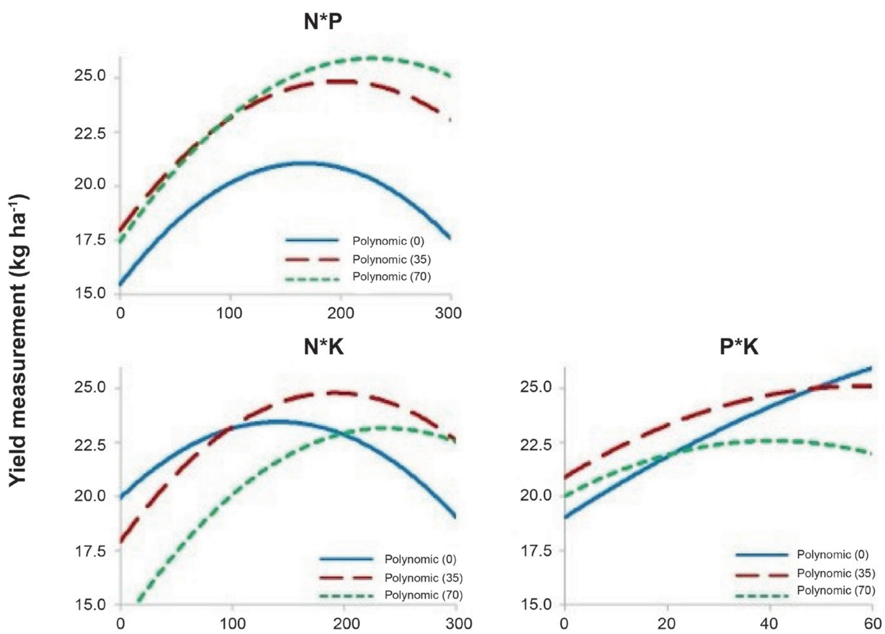


**Figure 3.** Interaction for broccoli yield.

Figure 4 shows a graphic representation of the quadratic models with the surface answer for the yield of broccoli crop.

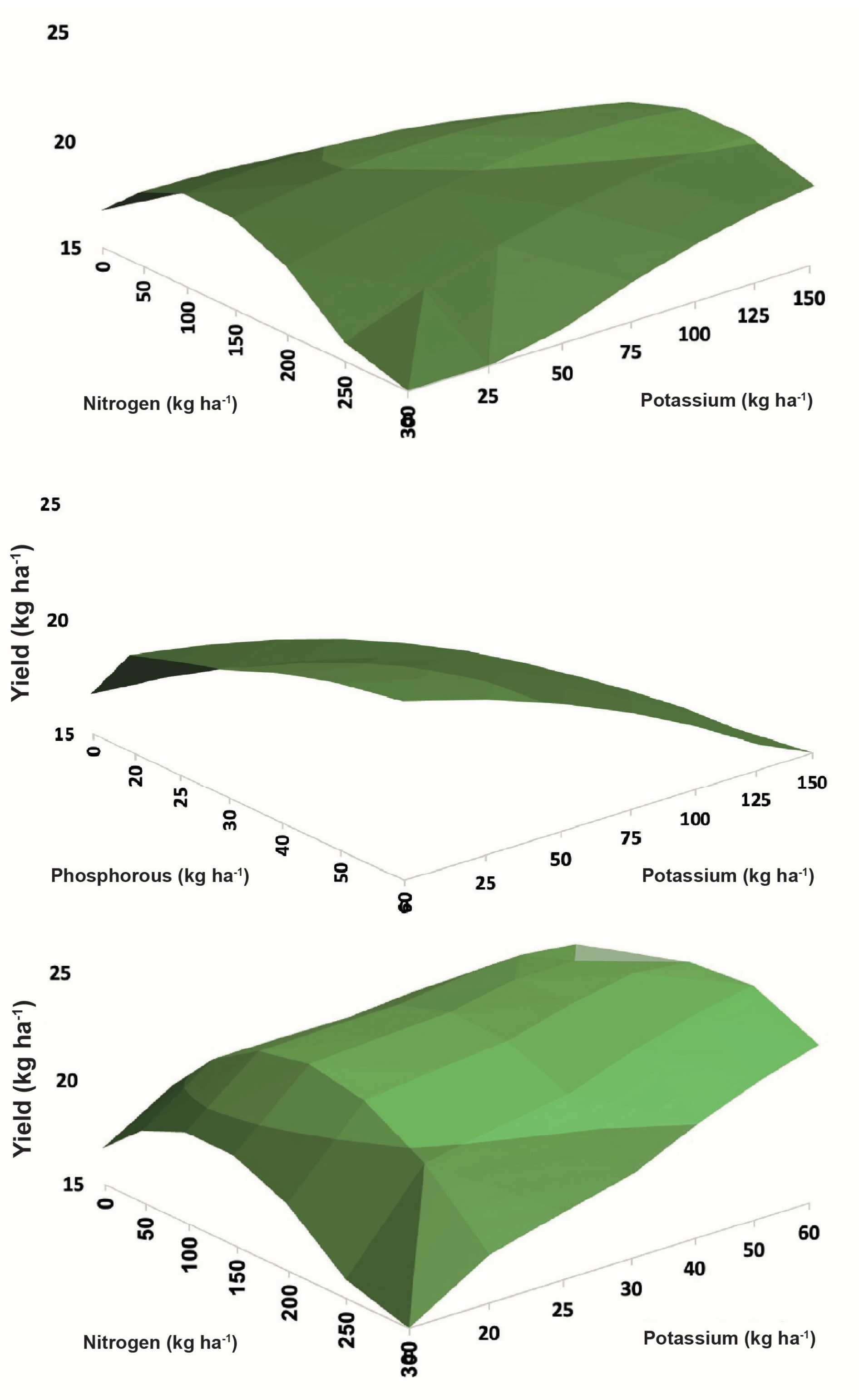


**Figure 4.** Response surface of the levels of a) N - P, b) P – K, and c) N - K, in broccoli yield.

The surface answer model for optimization to improve broccoli yield explored increasing levels of fertilization from 0 until 300 kg ha$^{-1}$ of N, 0 to 70 kg ha$^{-1}$ of P, and 0 to 180 kg ha$^{-1}$ of K, with the goal of reach the highest yield possible. The results showed that the application of 178 kg ha$^{-1}$ N, of 70 kg ha$^{-1}$ of P, and 25 kg ha$^{-1}$ of K, allowed to obtain a maximum yield of 26.35 t ha$^{-1}$ of broccoli (Table 11).

**Table 11.** Response optimization for broccoli yield.

| **Factor** | **Levels (kg ha$^{-1}$)** | | | **Maximum Yield (t ha$^{-1}$)** |
|---|---|---|---|---|
| | **Low** | **High** | Optimal | |
| N | 0 | 300 | 178 | |
| P | 0 | 70 | 70 | 26.35 |
| K | 0 | 180 | 25 | |

These results can be confirmed with studies done by Puenayan et al. (2008) and Lozano Fernández et al. (2018), who evaluated the effect of different levels and combinations of fertilizers with N, P and K in the development and production of broccoli crop. Their studies showed that higher doses than 225 kg ha$^{-1}$ of N tend to reduce crop yield. Although the maximum yield was obtained with doses of 250 and 400 ha$^{-1}$ of N, reaching 15 and 24.5 t ha$^{-1}$, respectively. Regarding P, the highest yield was reported with an application of 240 kg ha$^{-1}$, decreasing drastically with applications lower to 160 kg ha$^{-1}$. Moreover, it was observed a positive response with the application of 200 kg ha$^{-1}$ of K, while doses higher to 300 kg ha$^{-1}$ tend to decrease the production.

## 4. Conclusions

The research showed that the methodology of response surface is effective to optimize the chemical fertilization in broccoli hybrid crop Avenger in Ecuador. The results showed that the doses of 178 kg ha$^{-1}$ N, 70 kg ha$^{-1}$ P and 25 kg ha$^{-1}$ K provides the best yield, reaching 26.5 t ha$^{-1}$. This approach not only maximizes production, but it secures an efficient use of the fertilizers, potentially decreasing the costs and minimizing the environmental impact.

Moreover, the highest plant observed (59.90 cm) was obtained with 150 kg ha$^{-1}$ N, 70 kg ha$^{-1}$ P and 90 kg ha$^{-1}$ K; the best crown compaction (1.12 kg cm$^{-2}$) was obtained with 300 kg ha$^{-1}$ N, 35 kg ha$^{-1}$ P and 90 kg ha$^{-1}$ K; and the best equatorial diameter (197.80 mm) and yield (25.25 t ha$^{-1}$) were obtained with 239 kg ha$^{-1}$ N, 56 kg ha$^{-1}$ P and 144 kg ha$^{-1}$ K. These results showed the importance of properly adjust the fertilization doses to achieve a high-quality crop.

Finally, these results provide a solid base for future recommendations of fertilization in broccoli crop in the region, contributing to sustainability and profitability of the agricultural sector. Additional studies should also be conducted that consider other broccoli varieties and different agroclimatic conditions in order to validate and broaden the applicability of these results.

## Contributor roles

- Gloria Anabel Cornejo: investigation, resources, software, validation, writing – original draft, writing – review and editing.
- Yamil Everaldo Cartagena Ayala: conceptualization, methodology, software, validation, writing – review and editing.
- Rafael Parra: investigation, methodology, writing – original draft.
- Galo Hernán Puetate Huera: investigation, software, validation, writing – original draft, writing – review and editing.
- Francisco Hernán Chancusig: writing – original draft.
- Wilman Paolo Chasi Vizuete: writing – original draft.

## Ethical Implications

Ethics approval not applicable.

## Conflicts of Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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