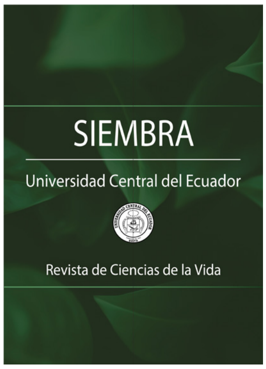
Effects of calcium and nitrogen on aphid (Brevicoryne brassicae) control on broccoli (Brassica oleracea var. italica) under two fertilization systems



Efectos del calcio y nitrógeno en el control de pulgón (Brevicoryne brassicae) en brócoli (Brassica oleracea var. italica) bajo dos sistemas de fertilización

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Abstract

Broccoli (*Brassica oleracea* var. *italica*) is a crop of high commercial value in Ecuador, whose productivity is often compromised by pests such as aphids (*Brevicoryne brassicae*). This study evaluated the effect of different nitrogen (N) and calcium (Ca) doses on the incidence of aphids under two fertilization systems: organic and conventional. Nitrogen promotes vegetative growth, although excess nitrogen limits flowering, while calcium strengthens cell walls, increasing tissue resistance. The study was conducted at the Nintanga company in Cotopaxi province (Ecuador), at 2,890 m a.s.l., in the "Santa Carmen" and "San Patricio" farms. A rotable central composite design was implemented, testing five levels of N and Ca (0, 75, 150, 225, and 300 kg ha^{-1}). Aphid incidence and plant height were recorded weekly over 13 weeks, with a planting density of 6.4 plants m^{-2}. Our results indicated that high doses of N combined with low levels of Ca significantly increased aphid incidence (up to 60%), especially in the organic system (average: 35%). In contrast, a balanced interaction between the two nutrients reduced aphid incidence to 14% in both systems. The conventional production system showed a lower average aphid incidence (20%) and greater homogeneity in the data Regression analysis revealed a positive effect of Ca on aphid incidence (coef=0.3646 in organic and 0.1496 in conventional), and a quadratic response of N, suggesting that high N doses may attenuate pest pressure, when properly balanced with Ca.

Keywords: *Brevicoryne brassicae*, organic fertilization, conventional fertilization, nutrient-induced resistance.

Resumen

El brócoli (*Brassica oleracea* var. *italica*) es un cultivo de alto valor comercial en Ecuador, cuya productividad se ve afectada por plagas como el pulgón (*Brevicoryne brassicae*). Esta investigación evaluó el efecto de distintas dosis de nitrógeno [N] y calcio [Ca] sobre la incidencia de esta plaga, bajo dos sistemas de fertilización: orgánico y convencional. El nitrógeno favorece el crecimiento vegetativo, aunque su exceso limita la floración; mientras que el calcio fortalece la pared celular, incrementando la resistencia de los tejidos. El estudio se realizó en la empresa Nin-

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tanga, provincia de Cotopaxi (Ecuador), a 2.890 m s.n.m., en los proyectos “Santa Carmen” y “San Patricio”. Se utilizó un diseño compuesto central rotable, con cinco niveles de N y Ca (0, 75, 150, 225 y 300 kg ha^{-1}). Durante 13 semanas se evaluaron semanalmente la incidencia del pulgón y la altura de planta, con una densidad de siembra de 6,4 plantas m^{-2}. Los resultados indicaron que altas dosis de N combinadas con bajas de Ca incrementaron significativamente la incidencia del pulgón (hasta 60%), especialmente en el sistema orgánico (promedio: 35%). En cambio, una interacción balanceada entre ambos nutrientes redujo la incidencia hasta un 14%. El sistema convencional presentó menor incidencia promedio (20%) y mayor homogeneidad en los datos. El análisis de regresión reveló un efecto positivo del Ca sobre la incidencia (coef. = 0.3646 en orgánico y 0.1496 en convencional), y una respuesta cuadrática del N, sugiriendo que dosis elevadas pueden atenuar su impacto sobre la plaga.

Palabras clave: *Brevicoryne brassicae*, fertilización orgánica, fertilización convencional, resistencia inducida por nutrientes.

1. Introduction

Broccoli (*Brassica oleracea* var. *italica*) is a vegetable in high demand both in the national and international markets. It is widely cultivated in various provinces of Ecuador, and its value lies not only in its nutritional properties, but also in its potential for disease prevention, which increased its economic and nutritional importance (Moreno et al., 2006; Raya-Montaño et al., 2018). Its production is, however, threatened by pests, such as the green aphid (*Brevicoryne brassicae*), that significantly affect crop yield.

Aphids feed on plant sap causing chlorosis, leaf deformation and curling; and, also creating favorable conditions for the proliferation of viral diseases. Their honeydew secretion promotes the development of fungi such as sooty mold, further aggravating the damage to the plant (Askar, 2021; Falcon-Alvarado et al., 2023). It is estimated that aphid infestation can reduce production by up to 30%, thus generating considerable economic losses for producers.

Within this context, mineral nutrition plays a key role in the productivity, and health of the crop. Calcium [Ca] is essential for the structural integrity of cell walls, and the regulation of physiological functions, while nitrogen [N] is indispensable for vegetative growth, protein synthesis, and chlorophyll formation (García Meléndez, 2022; Marschner, 2012). However, improper management of these nutrients, especially the excessive use of nitrogen fertilizers, can cause nutritional imbalances, soil salinity, and negative effects on both plant resilience and the environment (Carrillo-Riofrío & Minga-León, 2020; Jiménez Villalva & Osorio Bautista, 2019).

Various studies suggest that N is a limiting factor in broccoli production, recommending doses between 150 and 320 kg ha^{-1}, depending on the crop conditions (Cartagena Ayala, 2014; Pantoja, 2006; Román Llamuca, 2022). Specifically, Puenayan et al. (2008) report that 150 kg ha^{-1} is an optimal dose for maximizing the diameter of the head. Nonetheless, nitrogen efficiency depends on an adequate balance with Ca, as an excess of N in the absence of Ca can weaken the plant, and increase its susceptibility to pests such as aphids. This compromises both the commercial quality and the resistance of the crop to diseases.

In this sense, it is essential to evaluate how the interaction between N and Ca affects not only the yield but also the incidence of pests, considering different agricultural management systems.

The objective of this study was to evaluate the effect of N and Ca doses on aphid incidence, and agronomic variables of broccoli, comparing their behavior in two fertilization systems: organic and conventional.

2. Materials and Methods

2.1. Study Area

The study was conducted at Nintanga company, specifically on both the ‘Santa Carmen’ and the ‘San Patricio’ projects, located in the parish of Joseguango Bajo, Latacunga canton, of the province of Cotopaxi, Ecuador. The experimental area is located at an altitude of 2,890 m a.s.l., at the geographic coordinates. 00° 50’ 20.70” S y 78° 36’ 25.53” O (Figure 1).

The soil of the site showed a sandy loam texture, with a concentration of 25 mg kg^{-1} of nitrate nitrogen [N-NO_3], 5% organic matter, and a neutral pH of 7, suitable conditions for the development of broccoli cultivation.

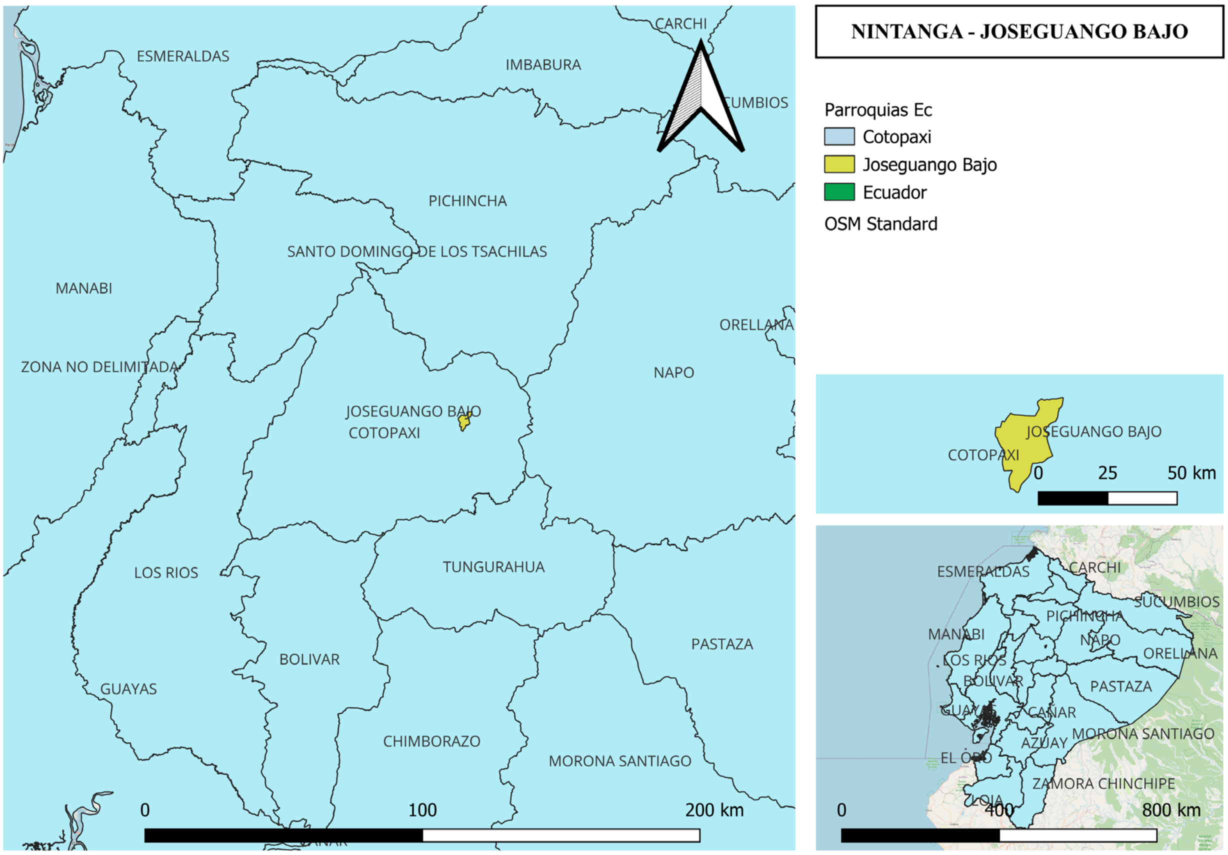

Figure 1. Location of the Santa Carmen and San Patricio projects in the province of Cotopaxi.

2.2. Experimental Design

The study was structured under a hierarchical factorial design, aimed at evaluating the effect of different doses of N and Ca on the incidence of aphid (*Brevicoryne brassicae*) and agronomic variables of broccoli cultivation (*Brassica oleracea var. italica*), based on two fertilization systems: organic and conventional.

Three factors were considered: the type of fertilization (the main qualitative factor, with two levels: organic and conventional), and the doses of N and Ca (quantitative factors, with five levels ranging from 0 to 300 kg ha^{-1} for both nutrients; Table 1), structured through a central composite rotatable design [CCRD], in the form of 2^k+1, where k represents the number of factors, with $k = 2$. Each system included 13 treatments derived from the CCRD (4 factorial, 4 axial, and 5 repetitions of the center point), in addition to two additional treatments: an absolute control (T14: 0 kg ha^{-1} of N and Ca) and a traditional control (T15: 200 kg ha^{-1} of N and 100 kg ha^{-1} of Ca), totaling 15 treatments per system. (Table 2).

Table 1. Levels of macroelements (N and Ca) in the Central Composite Rotable Design [CCRD].

Levels	Encoded Level		Actual Levels (Kg ha^{-1})	
	X_1	X_2	N	Ca
1	-α	-α	0	0
2	-1	-1	75	75
3	0	0	150	150
4	1	1	225	225
5	α	α	300	300

α = 1,41.

Table 2. *Treatments*.

Treatments	Encoded Level		Actual Levels (Kg ha^{-1})	
	X_1	**X_2**	**N**	Ca
T1	-1.00	-1.00	75	75
T2	-1.00	1.00	75	225
T3	1.00	-1.00	225	75
T4	1.00	1.00	225	225
T5	-1.41	0.00	0	150
T6	1.41	0.00	300	150
T7	0.00	-1.41	150	0
T8	0.00	1.41	150	300
T9	0.00	0.00	150	150
T10	0.00	0.00	150	150
T11	0.00	0.00	150	150
T12	0.00	0.00	150	150
T13	0.00	0.00	150	150
T14	-1.00	-1.00	0	0
T15	0.00	0.00	200	100

Each treatment was replicated four times, generating 60 experimental units per system and a total of 120. Each experimental unit consisted of a surface area of 10 m^2 (2 m × 5 m), formed by four furrows per plot, which allowed for uniform and representative agronomic management for the evaluation of treatments and data collection. Broccoli seedlings (*Brassica oleracea* var. *italica*) were used in the vegetative state, with three true leaves, 20 days old, and an average height of 5 to 8 cm at the time of transplanting. The planting was done with 0.80 m between furrows and 0.20 m between plants, achieving a population density of 64,000 plants ha^{-1}.

The evaluated variables were:

- Aphid incidence (%): percentage of infested plants per plot.
- Plant height (cm): measured at five phenological stages (V3, V10, VT, R1, and R3; that is, 30, 45, 60, 75, and 90 days after transplanting).
- Yield (t ha^{-1}): total weight of inflorescences per unit area, determined at harvest.

2.3. Management of fertilization

The study focused on evaluating the effects of different doses of N and Ca on broccoli cultivation, keeping the other essential nutrients constant across all treatments in order to exclusively isolate the effect of these two macronutrients. In the organic management system, compost was applied at a rate of 5 t ha^{-1} at the time of transplanting as the main source of nutrients. Subsequently, a reinforcement was carried out in week 4 with potassium sulfate [K_2SO_4] and agricultural gypsum [$CaSO_4$], and specific corrections were made in week 7 to maintain an adequate nutritional balance, according to soil conditions and the needs of the crop.

In the conventional management system, all treatments received a uniform base fertilization applied in week 2, consisting of triple superphosphate (46% P_2O_5), potassium muriate (60% K_2O), magnesium sulfate (27% MgO, 20% S), and Calcimed (30% CaO, 17% S). In addition, reinforcements were made in week 5, and corrections in week 8 to ensure a continuous supply of nutrients. The doses of N and Ca were adjusted according to the established experimental levels (0, 75, 150, 225, and 300 kg ha^{-1}), using fertilizers such as urea (46-0-0), potassium nitrate [KNO_3], and calcium nitrate [$Ca(NO_3)_2$].

2.4. Statistical analysis

A general linear model was used that integrated all treatments, allowing for the evaluation of both individual effects, and interactions between the type of fertilization and the doses of N and Ca. The type of fertilization was treated as a qualitative factor, while N and Ca were coded as quantitative variables, incorporating their linear, quadratic, and interactive effects. The adjusted statistical model is presented in the equation [1].

$$Y = \mu + F + \beta_1 * N + \beta_2 * Ca + \beta_{11} * N_2 + \beta_{22} * Ca_2 + \beta_{12} * (N \cdot Ca) + F \cdot N + F \cdot Ca + F \cdot N_2 + F \cdot Ca_2 + F \cdot (N \cdot Ca) + \epsilon \quad [1]$$

where:

- *Y*: response variable (incidence, height, or yield),
- *μ*: overall mean,
- *F*: effect of the type of fertilization (organic or conventional),
- *N·Ca*: coded doses of nitrogen and calcium,
- *β*: model coefficients,
- *ε*: experimental error

An analysis of variance [ANOVA] was performed for each variable, and in cases of significant differences ($p < 0.05$), Tukey's test at 5% was applied for mean comparison. In addition, response surface models [RSM] were adjusted within each fertilization system, allowing for the identification of optimal combinations of N and Ca that maximize yield and minimize aphid incidence, as proposed by Gutiérrez Pulido and Vara Salazar (2008).

3. Results and Discussion

3.1. Incidence of Aphid in crop

The ANOVA analysis (Table 3) showed significant effects ($p < 0.05$) of the type of fertilization, the doses of N and Ca, as well as their interactions, on the incidence of aphids (*Brevicoryne brassicae*). The interaction between fertilization and the quantitative factors (N and Ca) was also significant, indicating that the pest response varied according to the nutritional management system. On average, the organic fertilization system showed a higher incidence of aphids (21.84%), while in the conventional system it was considerably lower (5.26%). This suggests greater pest pressure under organic conditions, possibly due to the absence of synthetic agrochemicals. However, this higher incidence also showed a differential response to the combination of nutrients.

Table 3. Analysis of variance for aphid incidence in crops.*

Source of Variance	DF	SS	MS	F	p-value
C(Fertilization)	1	2016.8292	2016.8292	28117.7603	0
N_c	1	0.038	0.038	0.53	0.476
C(Fertilization): N_c	1	0.0628	0.0628	0.8756	0.3618
Ca_c	1	0.3095	0.3095	4.3149	0.0524
C(Fertilization): Ca_c	1	0.0038	0.0038	0.0535	0.8196
I (N_c ** 2)	1	0.0306	0.0306	0.4262	0.5221
C(Fertilization): I (N_c ** 2)	1	0.0081	0.0081	0.1134	0.7402
I (Ca_c ** 2)	1	0.0557	0.0557	0.777	0.3897
C(Fertilization): I (Ca_c ** 2)	1	0.0311	0.0311	0.4334	0.5186
N_c: Ca_c	1	0.0046	0.0046	0.0645	0.8023
C(Fertilization): N_c: Ca_c	1	0.0351	0.0351	0.4891	0.4933
Residual	18	1.2911	0.0717		
CV (%)					7.35
Mean (%)					13.45

* Degrees of freedom [DF], sum of squares [SS], mean square [MS], Fisher [F], p-value, mean, and coefficient of variation [CV%] calculated on the combined model, considering all treatments and both fertilization systems.

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The fitted response surface model for each system allowed the identification of specific combinations of N and Ca that minimized incidence. In the organic system, the lowest incidence was obtained with intermediate levels of N (150–200 kg ha^{-1}) and Ca (100–150 kg ha^{-1}). In the conventional system, the incidence remained low and relatively stable across the evaluated combinations. The coefficients of variation were low in both systems (0.38% in organic and 3.29% in conventional), indicating high experimental precision. The Tukey test showed statistically significant differences between treatments in the organic system, while in the conventional system, no marked differences were detected between combinations.

A highly significant effect of the type of fertilization on pest incidence was recorded ($p < 0.0001$), thus demonstrating that nutritional management systems have a decisive influence on the presence of *Brevicoryne brassicae*. In contrast, individual doses of N and Ca did not show significant effects ($p > 0.05$), although Ca exhibited a marginal trend towards significance ($p = 0.052$). The interactions between fertilization and quantitative factors also turned out to be non-significant, indicating that the pest's response to nutrients was consistent across both fertilization systems. The coefficient of variation [CV] indicates adequate precision of the experiment, which, together with the overall average incidence obtained, reinforces the reliability of the analysis performed and supports the robustness of the results obtained.

Overall, the data allow us to conclude that the type of fertilization is the main factor influencing the incidence of aphids, beyond the variations in the doses of N and Ca. This evidence is useful for decision-making in agronomic management, suggesting that the fertilization system plays an important role in the population dynamics of this pest.

3.1.1. Conventional System

Table 4 shows the estimated coefficients of the adjusted response surface model for the aphid incidence variable in the conventional fertilization system. The average observed value and low dispersion between treatments aligns with the general behavior observed in this system. The result for N (A) indicates that the increase in N doses does not significantly affect pest incidence. In contrast, Ca (B) showed a positive and statistically significant effect ($p = 0.0000$), demonstrating a higher sensitivity of the response variable to variations in this nutrient.

Table 4. Estimated effects for aphid incidence in conventional crops.*

Effect	Coefficient	EE	p-value	VIF
Mean	5.268	0.0507		
A: Nitrogen	0.0254	0.1029	0.6709	1.00
B: Calcium	0.2991	0.1034	0.0000	1.00
AA	-0.0718	0.1131	0.2654	1.07
AB	-0.0900	0.1455	0.2891	1.02
BB	-0.0560	0.1231	0.3773	1.07
Block	0.0000	0.0933	1.0000	

* The p-values come from the corresponding ANOVA. The term "Block" represents the repetition of the treatment.

The quadratic terms AA (N^2) and BB (Ca^2), as well as the interaction AB (N × Ca), exhibited low and non-significant coefficients ($p > 0.05$), thus their interpretation as relevant effects in this system is not justified. Their inclusion is due to the structure of the CCRD, but their permanence in the model does not represent a substantial contribution in predictive terms.

As to what regards the included factors, all values of the Variance Inflation Factor [VIF] remained close to 1, indicating that there are no collinearity issues among the terms in the model. The block was included as a control variable to represent the repetition in the experimental design (15 treatments × 4 repetitions), but its effect was null and non-significant ($p = 1.0000$), suggesting that the variability among repetitions was low and the experiment was adequately balanced.

The analysis of variance (Table 5) indicates that, in the conventional fertilization system, the only factor with a statistically significant effect on aphid incidence was Ca ($p = 0.0000$), with an F-ratio of 26.62. This shows that the increase in Ca doses is strongly related to a higher incidence of *Brevicoryne brassicae*.

Table 5. Analysis of variance of aphid incidence in conventional crops.*

Variance Source	DF	SS	MS	F	p-value
A: Nitrogen	0.0065	1	0.0065	0.18	0.6709
B: Calcium	0.8949	1	0.8949	26.62	0.0000
AA	0.0405	1	0.0405	1.22	0.2654
AB	0.0601	1	0.0601	1.15	0.2891
BB	0.0281	1	0.0281	0.77	0.3773
Blocks	0.0000	4	0.0000	0.0000	1.0000
Total Error	1.9444	55	0.0354		
Total corrected	2.9508	64			

* The only significant source was calcium. The quadratic and interactive terms did not have statistically significant effects (p > 0.05). The block had no effect, reflecting experimental control.

On the contrary, N, the quadratic terms (AA and BB), and the interaction N × Ca (AB) did not show statistical significance ($p > 0.05$), indicating that these factors do not have a relevant effect on the response variable in this system. Likewise, the effect of the blocks was null ($p = 1.0000$), confirming the homogeneity between repetitions. The low error and the total corrected sum of squares reflect low residual variability and adequate experimental precision.

Regarding the regression coefficients, the constant term (5.268) represents the estimated incidence of aphids under conditions of no fertilization, corresponding to the central points of the experimental design. The coefficient associated with N (0.0127) indicates a very slight positive effect on incidence, although it is statistically not significant ($p = 0.6709$), so it cannot be stated that this nutrient has a relevant influence on the behavior of the pest within the conventional system. In contrast, Ca showed a considerable positive effect (coefficient = 0.1496) and highly significant ($p = 0.0000$), showing that the increase in its dose is associated with an increase in aphid incidence. This finding positions Ca as the most influential factor in the adjusted model for this system. The quadratic terms corresponding to N (–0.0386) and Ca (0.0284), as well as the interaction N·Ca (–0.045), were not statistically significant ($p > 0,05$). Although these terms were maintained in the model due to the structure of the CCRD, their interpretation should be taken with caution, as they do not provide conclusive evidence of relevant curvatures or interactions from an agronomic or biological perspective.

As observed in Figure 2a, Ca (B) stands out as the factor with the greatest standardized effect, exceeding the threshold of statistical significance, which visually coincides with the results of the ANOVA ($p = 0.0009$). In contrast, the factors N (A), the quadratic terms (AA and BB), and the interaction (AB) show smaller effects and do not reach statistically significant levels ($p > 0.05$), reinforcing that their inclusion in the model responds more to the structure of the experimental design than to their actual impact on the variable. This visualization, therefore, coherently supports the findings obtained in the formal statistical analysis.

Figure 2b identifies one or more points clearly distant from the line, indicating the presence of outliers or possible deviations from the expected normality. Since the alignment of the points is not fully linear, it cannot be claimed that the normality assumption of the model is adequately met. This observation should be considered as a minor limitation of the fit. Despite this punctual deviation, the model may still be valid, especially if other conditions (such as homogeneity of variances and significance of the main effects) are met and robustness of the analysis has been verified under the other assumptions. Figure 2c represents the interaction between Ca and N doses on aphid incidence. Visually, a downward trend is observed in incidence as Ca doses increase (values > 1.0), while low levels of this nutrient (< -1.0) seem to be associated with higher levels of aphid incidence. For its part, N does not show a clear or uniform trend in relation to the response variable.

However, to support these visual observations, it is important to point out that the fitted statistical model supports this interpretation: the regression analysis showed that Ca was the only statistically significant factor ($p < 0.001$) in this system, while N and its interactions did not show significance ($p > 0.05$). Therefore, the response surface coherently illustrates the results of the model, but its interpretation must be anchored in the p-values of the analysis, and not considered on its own as conclusive evidence.

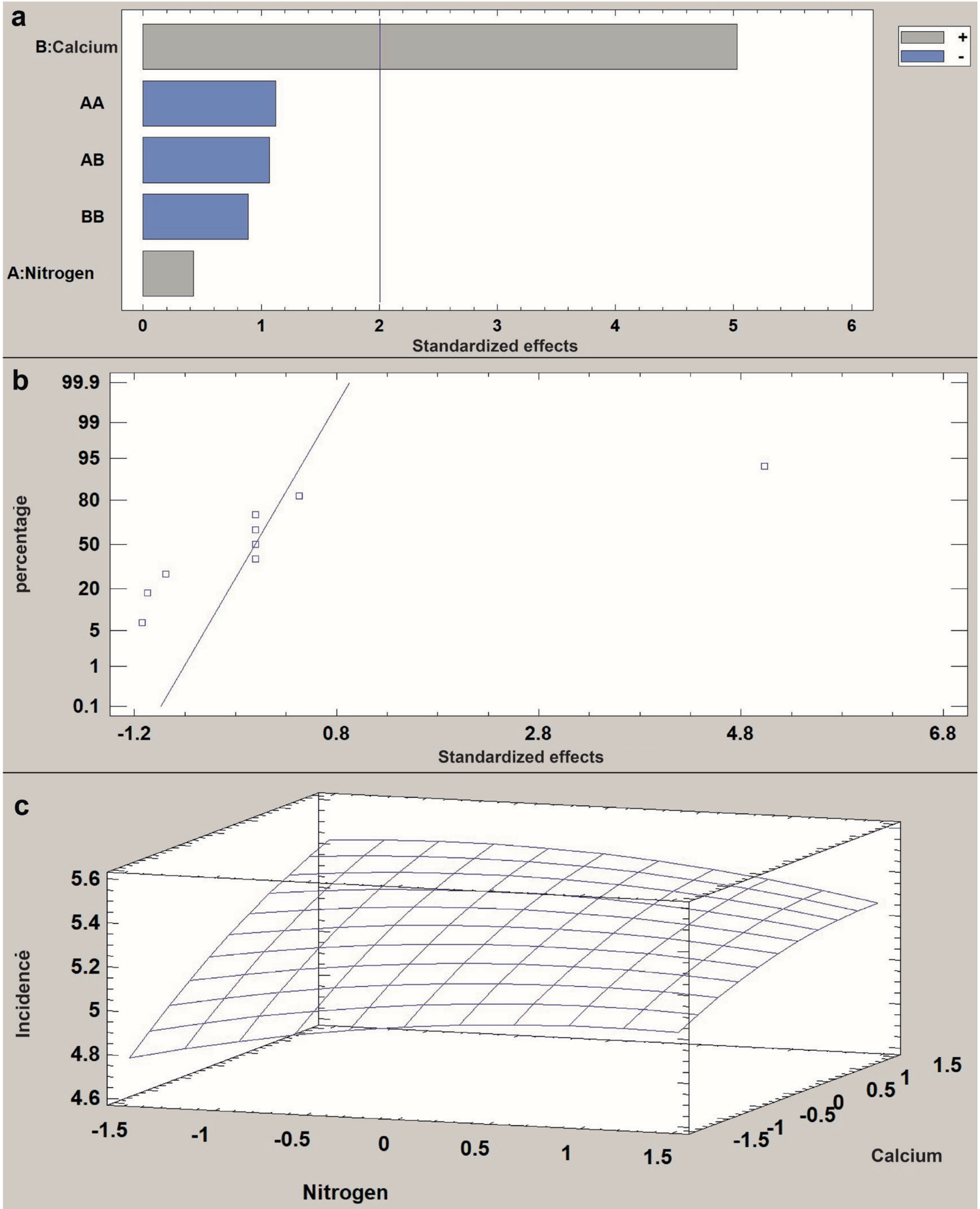

Figure 2. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for aphid incidence in conventional crops.

3.1.2 Organic System

The estimated coefficients (Table 6) were statistically significant ($p < 0.05$), indicating that both linear and quadratic effects, as well as the interactions of N and Ca, significantly influenced the incidence of the aphid. In particular, medium to high doses of N and Ca increased the presence of the pest, while the negative quadratic effects of both nutrients, as well as their negative interaction, suggest that high combinations of both partially reduce their individual impact. This reveals a non-linear behavior dependent on the combination of nutrients, which must be considered when designing fertilization schemes in organic systems.

The analysis of variance (Table 7) shows that all the factors included in the model had statistically significant effects ($p < 0.05$) on the incidence of aphids in the organic fertilization system. In particular, Ca and N had a highly significant impact. This confirms that both nutrients play an important role in pest response under organic conditions. The quadratic effects of N (AA) and Ca (BB) were also significant ($p = 0.0000$), indicating the presence of nonlinear relationships in incidence. Additionally, the interaction between N and Ca (AB) was significant ($p = 0.0000$), suggesting that pest response depends on specific combinations of both nutrients. The CV was 8.93%, reflecting an acceptable experimental variability. The low mean error also supports the accuracy of the fitted model.

Table 6. Estimated effects for aphid incidence in organic crops.

Effect	Coefficient	EE	p-value	VIF
Mean	21.844	0.0261		
A: Nitrogen	0.354351	0.0413	0.00	1.0
B: Calcium	0.364602	0.0413	0.00	1.0
AA	-0.300252	0.0424	0.00	10.731
AB	-0.48	0.0584	0.00106	1.0
BB	-0.365252	0.0425	0.00	10.731
block	0.0	0.0557	1.0	12.466

Table 7. Analysis of variance of aphid incidence in organic crops.

Source of Variance	SS	DF	MS	F	Value-P
A: Nitrogen	12.557	1	12.557	28.97	0.0000
B: Calcium	13.294	1	13.294	30.61	0.0000
AA	0.7839	1	0.7839	18.05	0.0000
AB	0.5187	1	0.5187	11.95	0.0000
BB	0.6888	1	0.6888	15.86	0.0000
Blocks	0.186	4	0.0465	1.07	10.000
Total Error	23.792	55	0.0434		
Total (corr.)	6.262	64			

Regarding the regression coefficients (equation [2]), the constant term (21.844) represents the estimated average incidence of aphids in the absence of fertilization, corresponding to the central point of the experimental design. This value reflects a higher pest pressure under organic conditions compared to the conventional system. The coefficients for N and Ca indicate a significant positive effect ($p = 0.0000$), suggesting that as the dose of these nutrients increases, so does the incidence of aphids. The quadratic effects of both nutrients were negative and significant for N^2 and Ca^2, indicating the existence of an optimal dose point, beyond which a higher concentration leads to a decrease in the incidence of aphids. This nonlinear behavior suggests a saturating or self-limiting effect of the system. The N·Ca interaction was also significant, revealing that the combination of high doses mitigates the individual effectsThe N·Ca interaction was also significant, revealing that the combination of high doses mitigates the individual effects of these nutrients, reducing the incidence of the pest. Together, these results show a more complex and responsive reaction of the organic system to the dynamics of nutrients, where both individual effects and their combinations significantly affect the variable under study.

$$Incidence\ of\ Aphid = 21{,}844 + 0{,}1772N + 0{,}1823Ca - 0{,}1501N^2 - 0{,}2400(N \cdot Ca) - 0{,}1826Ca^2 \quad [2]$$

The standardized Pareto diagram (Figure 3a) shows that all the factors included in the model had a significant effect on aphid incidence. In this system, both Ca (B) and N (A) reached standardized values close to or greater than 8.0, indicating a high individual influence on the response variable. Likewise, the quadratic terms (AA and BB) and the interaction (AB) also exceeded the significance threshold, indicating that the relationship between the factors and incidence is not linear and that there are relevant combined effects. This graphical representation is in complete agreement with the results of the statistical analysis, where all coefficients were statistically significant ($p < 0.01$).

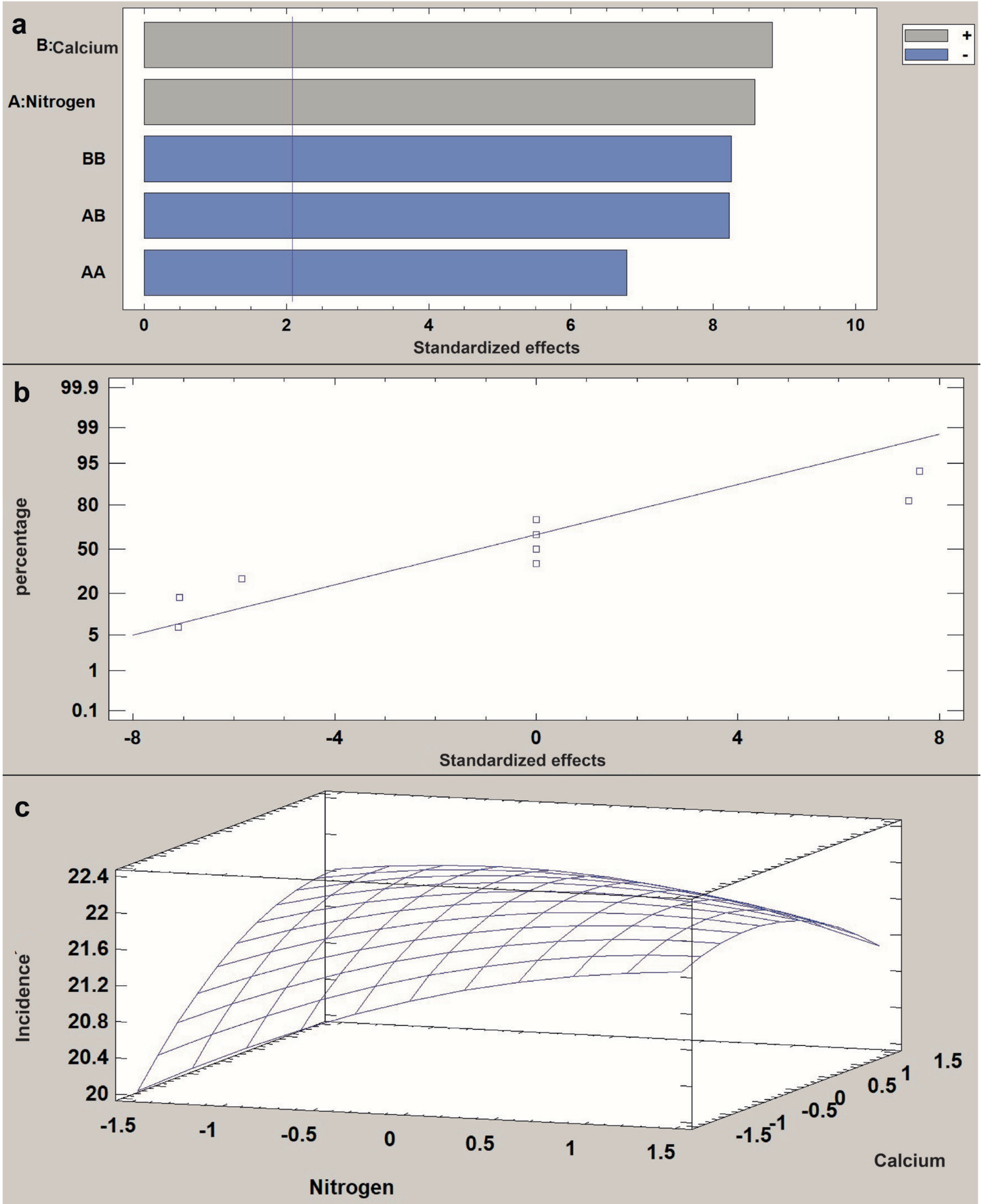

Figure 3. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for aphid incidence in organic crops.

In the normal probability graph, a greater dispersion of points along the line is observed compared to the conventional system, with standardized effects ranging from -4.2 to 7.9 (Figure 3b). Although there are no extremely distant points, the dispersion indicates that normality is not completely evident; the observed behavior suggests a reasonable fit, albeit with greater variability than in the conventional system. The response surface (Figure 3c) allows us to visualize how the incidence of aphids behaves in response to different combinations of N and Ca. In this system, an upward response is observed with the increase of N, with values exceeding 22% at the highest doses. This trend coincides with the statistical analysis, where N had a significant effect on the variable. ($p < 0.001$).

Additionally, a pronounced curvature is observed in the surface, which reflects the influence of quadratic and interactive effects, also confirmed as significant in the model. Altogether, the graph supports the conclusion that, under organic conditions, the incidence of aphids is determined not only by the individual effects of the nutrients but also by their combinations, highlighting the need for more precise nutritional management to control the infestation in this system.

3.1.3. Comparison between systems

The results obtained in the two fertilization systems evaluated (organic and conventional) showed clear differences in the behavior of aphid (*Brevicoryne brassicae*) incidence in response to the application of N and Ca. In the conventional system, regression and variance analysis showed that only Ca had a statistically significant effect on incidence, with a positive coefficient (0.1496), suggesting a progressive increase in the pest as the dose of this nutrient increases. In contrast, N and its combinations did not show relevant effects, indicating that aphid development in this system is not significantly modulated by this macronutrient.

In the organic system, a more complex pattern was observed. Both N and Ca, along with their quadratic and interactive terms, showed statistical significance ($p < 0.05$), indicating higher sensitivity to the interaction between nutrients. This is related to a more active dynamic of biological factors, such as natural enemies of aphids or soil microbiota, whose presence is more notable in organically managed soils. (Costa et al., 2023; Guerrieri & Digilio, 2008).

Furthermore, studies such as that of Rahman (2022) highlight that excess N can induce greater vegetative growth, increasing plants' susceptibility to insect attacks such as aphids. This aligns with the results of the present study, where an initial increase in incidence was observed with the increase of N, followed by a decrease at high doses, as suggested by the negative quadratic terms ($N^2 = -0.1501$, $Ca^2 = -0.1826$). On the other hand, Maldonado and Calvache Ulloa (2006) and Pantoja (2006) have demonstrated that the unbalanced use of nutrients can generate negative effects on crop health, reaffirming the importance of maintaining optimal nutritional relationships.

Likewise, Dixon (2012) and Blackman and Eastop (2000) point out that nutritional availability influences the population behavior of aphids, as it affects both host quality and the reproductive efficiency of the insect. In this sense, the higher incidence observed in the organic system may be due to lower chemical control pressure and a more favorable environment for colony establishment, as mentioned by Askar (2021) and Falcon-Alvarado et al. (2023).

From an agronomic perspective, these findings highlight that in organic systems, fertilization management must be more precise, as small variations in dosage can trigger nonlinear responses in pest incidence. In contrast, in conventional systems, behavior is more stable and controlled, with less variability and primarily dependent on Ca as a determining factor.

3.2. Height of the plant

3.2.1. Conventional System

The height of the plant in the conventional system showed progressive growth from 13.75±5.29 cm at 30 days after transplant (DAT) to 58.48±0.98 cm at 90 DAT, as shown in Table 8. The variation in the CV indicates a suitable experimental precision, especially in the final stages of development. The differences between treatments were statistically significant at 75 DAT ($\alpha = 0.05$), with T5 recording the highest height (62.93 cm), and at 90 DAT, T9 (63.22 cm), T7 (63.05 cm), and T5 (62.93 cm) had the highest heights. These differences suggest that, under the conventional system, some treatments significantly favored growth in advanced stages, especially in nutrient combinations that included high levels of Ca and N. In the other evaluations (30, 45, and 60 DAT), no relevant differences were found ($\alpha > 0,05$).

The Pareto diagram (Figure 4a) shows that N (A) is the factor with the greatest influence on plant height at 75 DAT, with a standardized effect close to 4.0. The interaction AB (N·Ca) is even more notable, exceeding the significance threshold and reaching the highest effect in the graph. The interactions AA (N^2) and BB (Ca^2) also have minor but significant effects. In contrast, Ca (B) shows a more moderate influence (≈1.5), suggesting that its direct impact on height is less than that of N, although it is relevant when combined with it.

Table 8. Average plant height and Tukey's test at 75 and 90 DAT in conventional crops.

Treatments	Plant height (cm)				
	30 DAT	**45 DAT**	**60 DAT**	**75 DAT**	**90 DAT**
T1	14.12	24.95	44.43	56.88[a]	62.08[a]
T2	15.05	25.88	44.22	55.82[a]	62.53[a]
T3	16.12	25.50	44.18	54.31[a]	61.76[a]
T4	14.36	23.78	46.94	56.40[a]	62.74[a]
T5	16.58	24.28	46.73	56.73[b]	62.93[ab]
T6	15.76	24.27	46.67	55.10[b]	61.99[a]
T7	16.06	23.17	46.73	56.65[a]	60.79[ab]
T8	14.56	24.48	45.20	54.85[ab]	62.00[ab]
T9	15.25	24.31	45.56	56.17[a]	61.22[ab]
T10	15.06	24.61	45.96	55.97[ab]	62.81[a]
T11	15.07	24.84	46.03	55.32[a]	60.22[a]
T12	16.37	23.92	44.84	54.80[a]	62.38[a]
T13	16.16	25.02	45.69	54.08[ab]	62.83[a]
T14	10.28	19.17	27.69	36.31[b]	42.41[a]
T15	15.56	24.56	44.70	56.03[ab]	62.73[ab]
Mean	13.75	26.11	48.65	56.36	58.48
SD	5.29	2.51	1.29	1.51	0.98
CV (%)	5.29	2.51	1.29	1.51	0.98

The normal probability plot (Figure 4b) shows an acceptable fit to the theoretical line, with values ranging from -4 to 4 in standardized effects. Most points are closely aligned with the line, indicating that the model residuals follow an approximately normal distribution, validating the consistency of the statistical analysis. The presence of a few points far from the line suggests controlled variability and does not represent a critical violation of the normality assumptions. In the response surface, a decreasing trend in height is observed as N increases, especially when Ca doses are low (Figure 4c). This suggests that high doses of N, without a proper balance with Ca, negatively affect growth, possibly due to inhibition in the absorption of other nutrients or an osmotic imbalance. On the other hand, moderate levels of Ca seem to mitigate the negative effect of N, stabilizing the height of the crop. The surface indicates that the joint management of both nutrients is crucial for optimizing growth. These findings reinforce the need for nutritional balance, beyond simply increasing a single fertilizer.

3.2.2. Organic System

The average height of the plants progressively increased from 15.63±3.86 cm at 30 DAT to 62.07±1.81 cm at 90 DAT, reflecting a consistent and expected growth pattern throughout the cycle (Table 9). The fluctuation of the CV indicates adequate experimental precision at the different stages of evaluation. Significant differences were observed between treatments at 75 DAT ($\alpha = 0.01$), when the heights varied between 14.76 cm (T2) and 57.63 cm (T6), and at 60 DAT ($\alpha = 0.05$), while no statistical differences were detected in evaluations conducted at 30, 45, and 90 DAT ($\alpha > 0.05$), according to Tukey's test. At 90 DAT, T1 achieved the highest height, corresponding to the traditional combination used by the producer under an organic system, with doses of 200 kg ha^{-1} of N and 100 kg ha^{-1} of Ca. These results suggest that this management favors growth in the advanced stages of development.

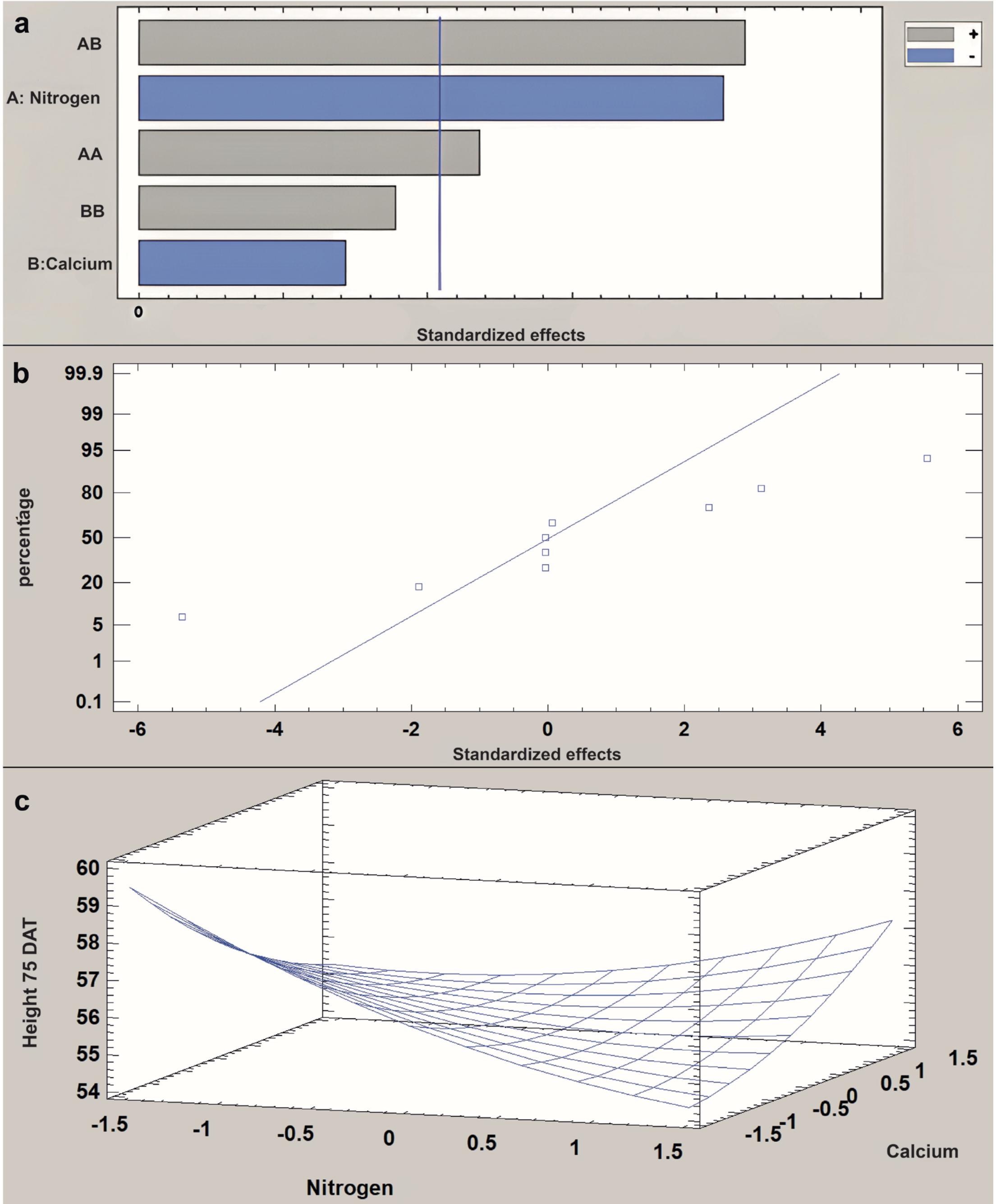

Figure 4. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for plant height in conventional crops.

3.2.2. Organic System

The average height of the plants progressively increased from 15.63±3.86 cm at 30 days after transplanting (DAT) to 62.07±1.81 cm at 90 DAT, reflecting a consistent and expected growth pattern throughout the cycle (Table 9). The fluctuation of the CV indicates adequate experimental precision at the different stages of evaluation. Significant differences were observed between treatments at 75 DAT ($\alpha = 0.01$), when the heights varied between 14.76 cm (T2) and 57.63 cm (T6), and at 60 DAT ($\alpha = 0.05$), while no statistical differences were detected in evaluations conducted at 30, 45, and 90 DAT ($\alpha > 0.05$), according to Tukey's test. At 90 DAT, T1 achieved the highest height, corresponding to the traditional combination used by the producer under an organic system, with doses of 200 kg ha^{-1} of N and 100 kg ha^{-1} of Ca. These results suggest that this management favors growth in the advanced stages of development.

Table 9. Average plant height and Tukey's test at 75 and 90 DAT in organic crops.

Treatments	Plant Height (cm)				
	30 DAT	**45 DAT**	**60 DAT**	**75 DAT**	**90 DAT**
T1	14.98	26.62	47.39	55.88[a]	59.72[a]
T2	14.76	25.37	48.89	57.63[a]	57.84[a]
T3	14.06	26.15	45.92	55.91[a]	59.06[a]
T4	14.76	26.78	47.54	55.07[a]	58.20[a]
T5	14.91	25.08	46.86	56.37[a]	57.26[a]
T6	13.57	26.47	49.07	56.29[a]	57.56[a]
T7	13.27	26.33	49.17	55.21[a]	57.94[a]
T8	14.41	26.90	48.63	55.57[a]	59.86[a]
T9	13.91	26.49	45.53	56.63[a]	58.70[a]
T10	13.00	25.81	49.28	56.11[a]	58.42[a]
T11	14.90	25.15	49.11	56.29[a]	59.06[a]
T12	13.69	26.87	49.64	55.20[a]	57.53[a]
T13	13.28	26.24	49.73	57.61[a]	58.72[a]
T14	12.00	23.80	28.17	36.71[c]	42.81[c]
T15	14.51	25.42	45.29	56.72[a]	57.92[a]
Mean	15.63	25.37	45.46	55.25	62.07
SD	3.86	1.73	1.29	1.51	1.81
CV (%)	3.86	1.73	1.29	1.51	1.81

The Pareto diagram (Figure 5a) reveals that the interaction between N and Ca (AB) is the factor with the greatest effect on plant height, with a standardized value close to 4. This is followed by the quadratic effect of Ca (BB) and the main effect of N (A), both with significant effects. On the other hand, Ca (B) and the quadratic term of N (AA) show effects below the significance threshold, indicating that their individual influence is limited. These results reinforce the idea that the interaction between nutrients plays a more decisive role than isolated factors, highlighting the need to optimize their ratio in organic systems.

In the normal probability graph, a general linear trend is observed, indicating that the model's residuals follow an approximately normal distribution, validating the adequacy of the statistical model employed (Figure 5b). However, the presence of some points far from the central line suggests that there may be unconsidered factors in the model, or a certain degree of variability not explained by the included terms. This could be associated with specific conditions of the organic system, such as variability in nutrient mineralization or interaction with the soil microbiome. Compared to the conventional system, the response surface shows greater stability in the plant's response to variations in the doses of both nutrients (Figure 5c). Although a decreasing trend in height is maintained when N is high and Ca is low, this decrease is less pronounced. This suggests that the organic system offers. This suggests that the organic system offers a greater buffering capacity against nutritional imbalances, possibly due to the plant's adaptive mechanisms or the gradual release of nutrients over time. The surface also indicates that a balanced management between both factors favors stable crop growth under organic conditions.

3.2.3. Comparison between systems

The height growth of the plants showed clear differences between the organic and conventional fertilization systems. In both, an upward trend was observed throughout the crop cycle, but with important nuances in the response to the treatments. In the organic system, the differences between treatments were statistically significant at 60 and 75 DAT, while in the conventional system, significance was only evident at 75 DAT, suggesting a later and more concentrated response of the crop under conventional management.

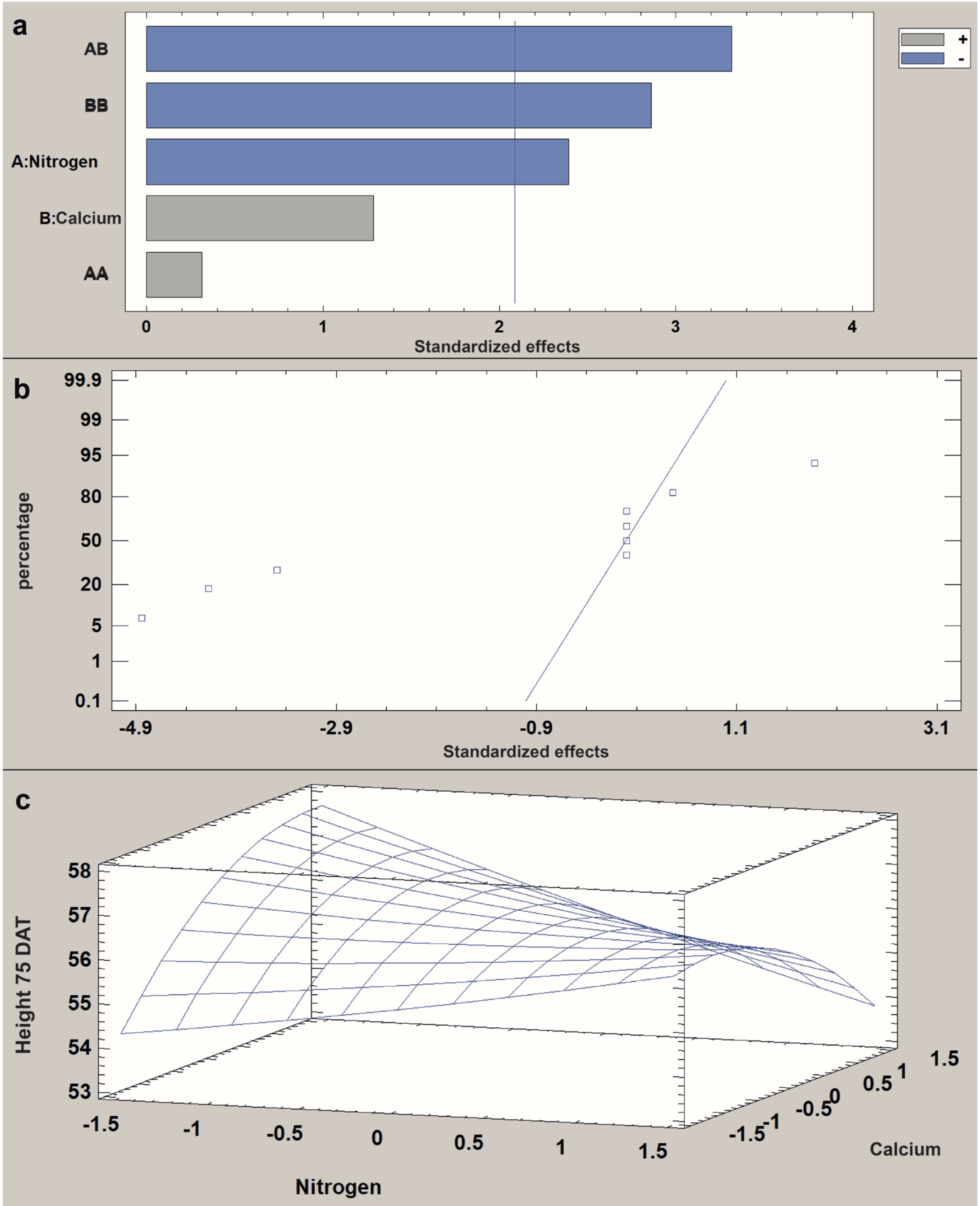

Figure 5. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for plant height in organic crops.

In general terms, the final heights were similar between both systems, with average values close to 62 cm at 90 DAT. However, in the conventional system, less dispersion was observed (CV ≤ 1.0%), reflecting greater uniformity in growth among treatments. In contrast, the organic system showed greater variability, possibly related to differences in nutrient availability and their slower release in the soil.

These results are consistent with studies such as those by Bacarreza Manrique (2018), where variability in broccoli height was evidenced as influenced by nutritional management and genotype. Similarly, Mainardi Fazio (2017) emphasizes that N is determinant for the vegetative growth of broccoli, especially in early stages, although excess nitrogen can negatively affect the balance with flowering. In the organic system, this sensitivity to dosage became evident more clearly. Furthermore, environmental factors such as night temperature, planting density, and solar radiation, discussed by Rodríguez-González et al. (2020), may also have influenced the growth dynamics, particularly in the conventional system, where nutritional control was more precise.

Therefore, it is concluded that plant height is affected not only by the type of fertilization but also by the synchronization between nutrient availability and the phenological phases of the crop.

3.3. Yield and Inflorescence production

Differences in inflorescence production were observed under organic and conventional fertilization systems, evaluated using ANOVA. In the organic system, the mean square for treatments was 0.58, with a total error of 0.57 and a CV of 4.00%, suggesting slight variability between treatments but with acceptable experimental precision. In the conventional system, the mean square was slightly lower (0.55), and the total error also decreased to 0.42, with a lower CV (1.91%), indicating greater homogeneity and consistency in the data obtained for this system. The average yield was higher in the conventional system (21.27 t ha^{-1}) compared to the organic system (18.95 t ha^{-1}), which reinforces the idea that conventional fertilization generates a more uniform and efficient response in terms of floral biomass production (Table 10).

Table 10. Organic and conventional broccoli inflorescence production.

Collection (DAT)	Total Weight ($t\ ha^{-1}$)		Number of collected inflorescences ($N°\ ha^{-1}$)		Average weight ($g\ inflorescence^{-1}$)	
	Organic	Conventional	Organic	Conventional	Organic	Conventional
87	3.6	4	12.800	12.800	600	700
90	10.8	12	38.400	38.400	700	750
93	3.6	4	12.800	12.800	550	650
LSD 15%	2.7	3	9.600	9.600	100	100
TOTAL	18	20	64.000	64.000		

3.3.1. Conventional System

Regarding the main effects, N showed a slight negative effect (-0.14432), indicating that its increase does not significantly favor production. On the other hand, Ca had a more pronounced negative effect (-0.941246), suggesting that its application could reduce the production of inflorescences in this system. The interactions between factors presented variable values: AA (-0.634753) and BB (-0.0247497) were negative, while AB (0.135) had a slightly positive effect. However, the magnitude of these coefficients indicates that the interactions, in general, do not have a substantial impact. Additionally, the VIF values obtained, close to 1, rule out collinearity problems among the factors included in the model.

Regarding the analysis of variance, it is confirmed that Ca was the only factor with a highly significant effect ($p = 0.0000$) on inflorescence production. In contrast, N did not show significance ($p = 0.3970$), and thus its effect on the response variable is not relevant in this system. The quadratic interaction of N (AA) was also significant ($p = 0.0020$), suggesting that the response to this nutrient is not linear, and there may be an optimal dose to maximize production. Interactions AB ($p = 0.5734$) and BB ($p = 0.8913$), on the other hand, were not significant. The blocking factor also showed no relevant differences ($p = 1.0000$), indicating low variability between repetitions. Ca is identified as the most influential and statistically significant factor in inflorescence production under a conventional system, while N and most interactions do not present relevant effects, with the exception of the quadratic term. of N, which deserves greater attention in future evaluations.

As for the regression coefficients, the constant term (21.276) represents the average yield in the absence of N and Ca application. The negative coefficient of N (-0.07216) indicates that, in this system, its increase tends to slightly reduce production, being statistically insignificant. This trend is more pronounced for Ca (-0.470623), whose significant negative effect suggests that high doses could adversely affect the production of inflorescences. The quadratic effects AA (-0.317376, significant) and BB (-0.012374, not significant) reinforce the non-linear nature of the crop's response to both nutrients, while the interaction AB (0.0675) shows a mild positive effect, although not significant, which could indicate a favorable combined effect at certain ratios.

The Pareto diagram (Figure 6a) shows that Ca is the factor with the greatest effect on flower production in the conventional system, with a standardized value close to 6.0. This is followed by the quadratic effect of

N (AA) with an intermediate influence. N as the main factor has a moderate impact, while the interactions AB and BB present reduced effects. These visual results are consistent with the previous statistical analysis, where Ca and the quadratic terms were statistically significant, confirming their role as key determinants in the productive response.

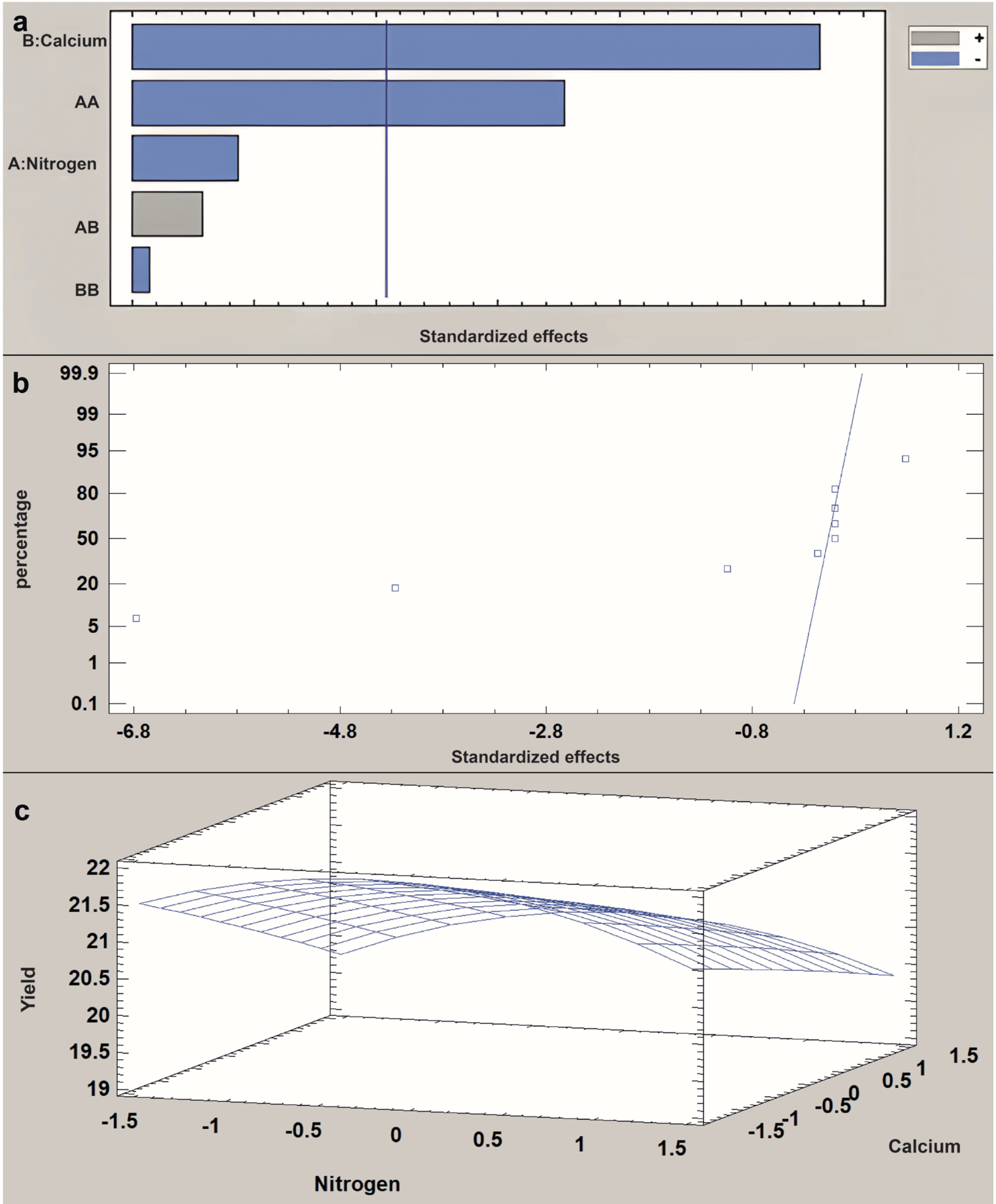

Figure 6. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for inflorescence production in conventional crops.

The normal probability graph (Figure 6b) shows a partial alignment of standardized effects with the theoretical line. Although most points follow the expected trend, there are extreme values deviating from the line, indicating possible deviations from normality. This dispersion suggests that some effects are influenced by unmodeled sources of variation, or that certain treatments have a particularly high or low impact on the response. The response surface (Figure 6c) reflects a positive response at intermediate and high levels of Ca, with yields exceeding 20.5 t ha^{-1}. In contrast, low levels of Ca (< -1.0) are associated with a decrease in harvested biomass. N, while having a less pronounced effect, interacts with Ca in certain ranges, suggesting that the balance between both nutrients is key to optimizing production. The model confirms that Ca is the most influential factor in the conventional system. aligned with the estimated effects and the results of the variance analysis.

3.3.2. Organic System

The main factors, N and Ca, had negative coefficients estimated in the adjusted model (-0.135061 and -0.31905, respectively), suggesting that increases in their application could slightly reduce the production of inflorescences. Ca had a less pronounced effect compared to the conventional system. The quadratic and combined interactions showed more relevant variability: AA (-0.300252) and BB (-0.480), reflecting significant negative effects, especially BB, which could indicate that a high dose of Ca has a reducing impact on production. The interaction AB (0.147249) showed a slight positive effect, possibly without statistical significance. VIF values close to 1 rule out collinearity problems, except for block (1.6), which could be contributing to some variability unexplained by the main factors.

The ANOVA supports these observations. The N ($p = 0.0064$), Ca ($p = 0.0348$), and the quadratic terms AA ($p = 0.0046$) and BB ($p = 0.0408$) were statistically significant ($p < 0.05$). In contrast, the interaction AB ($p = 0.0610$) was not significant, suggesting that the combined effects between N and Ca are less relevant than their individual or quadratic effects. The block factor again showed no significant influence ($p = 1.0000$), indicating a low effect of variability between repetitions.

The constant of the regression model (equation [3]) represents the average production value in the absence of N and Ca application. The main factors, N ($p = 0.0064$) and Ca ($p = 0.0348$), showed significant negative effects, indicating that increases in their doses reduce the production of inflorescences under this fertilization system. However, the effect of Ca was less pronounced than that of N. Regarding the quadratic terms, AA ($p = 0.0046$) showed a positive and significant effect, suggesting that there are optimal levels of N that could favor production if carefully adjusted. In contrast, BB ($p = 0.0408$) had a negative significant effect, reinforcing the idea that high doses of Ca could be counterproductive. The interaction N·Ca (AB) was not significant ($p = 0.0610$), although its negative coefficient (-0.24) could indicate a tendency towards reduction in response when both nutrients are combined at high levels. This result suggests that, although each factor separately has an important effect, their combination does not generate a clear synergistic impact on production.

$$Production\ of\ inflorescence = 18{,}954 - 0{,}06753N - 0{,}01595Ca + 0{,}07362N^2 - 0{,}19888Ca^2 \quad [3]$$

In contrast to the conventional system, the Pareto diagram (Figure 7a) reveals that the quadratic interaction BB is the factor with the greatest standardized effect, followed by the interaction AB. Both factors outweigh the influence of the main effects of N and Ca. This suggests that, under organic fertilization conditions, the interactions between nutrients gain greater relevance than their individual effects. Specifically, the combination of high or low doses of N and Ca significantly modifies biomass production. This pattern highlights the need to carefully consider the synergies or antagonisms between nutrients when making agronomic recommendations.

The normal plot (Figure 7b) shows that most points follow a trend close to the theoretical line, with standardized effects ranging approximately from -2.3 to 1.7. Although some outliers deviate from the fitting line, they do not significantly affect the validity of the model. The overall distribution is acceptable, indicating that the regression model fits the experimental data reasonably well, although it could benefit from the inclusion of other variables to reduce the observed dispersion at the extremes. The response surface (Figure 7c) shows a positive trend in broccoli biomass with high levels of N (> 1.0), reaching yields above 19.5 t ha-1. Conversely, low levels of N are associated with reduced production. Ca, for its part, presents a stabilizing effect: its influence is not as pronounced as that of N, but it contributes to maintaining consistent production when applied at the intermediate levels (0 a 1.0). This behavior suggests that, in organic systems, N is a direct limiting factor, while Ca acts as a modulator of nutritional balance.

3.3.3. Comparison between systems

The yield of inflorescences also showed notable differences between systems. In the conventional system, higher values were achieved (21.27 t ha^{-1}) compared to the organic system (18.95 t ha^{-1}), although the total number of inflorescences collected was identical (64,000 inflorescences ha^{-1}), suggesting that the difference mainly lies in the average weight per unit. The weight in the conventional system varied between 650 and 750 g, while in the organic system it ranged from 550 to 700 g. The statistical analysis confirmed greater homogeneity in the yield of the conventional system, with a CV of 1.91%, compared to 4.00% in the organic system. This stability could be due to greater availability and absorption of nutrients in the conventional system, particularly N and Ca, which favored a more efficient accumulation of biomass in the inflorescences.

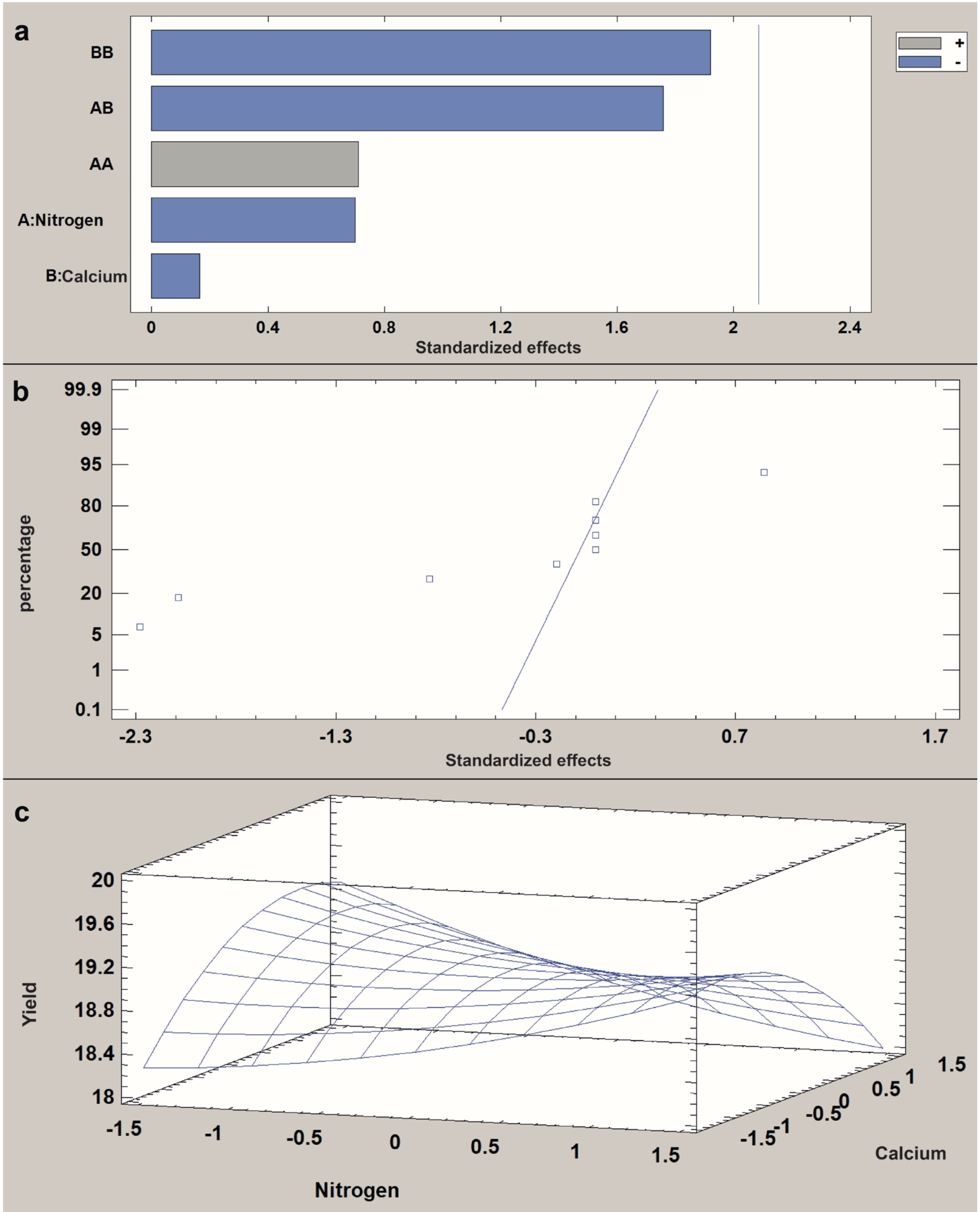

Figure 7. Standardized Pareto diagram (a) and Normal probability (b) and Response surface (c) for inflorescence production in organic crops.

Studies like those of Puenayan et al. (2008) and Román Llamuca (2022) had already pointed out that adequate doses of N, combined with good management of K and Ca, increase the weight of the heads. However, the excess of any of these nutrients, especially N, can lead to excessive vegetative growth to the detriment of yield (Cartagena Ayala, 2014). In this research, the regression analysis showed that in the conventional system, Ca had a significant negative effect on production, while in the organic system the impact was more moderate, although with greater interactive and quadratic effects. This suggests that the organic system responds more complexly to the combination of nutrients, and that fertilization management in these crops requires more careful planning to avoid imbalances that may affect the filling and size of the inflorescences. As indicated by Marschner (2012) and White and Broadley (2003), the balance between nutrients is essential not only for growth but also for the quality of the harvestable organ, as confirmed in this assessment.

3.4. General discussion

The results obtained in this research confirm that the type of fertilization system (organic vs. conventional) significantly influences the behavior of broccoli crops (*Brassica oleracea* var. *italica*), both in agronomic variables and in pest incidence. The differences between the two systems were not limited to average values, but also to the response pattern to N and Ca doses and their respective interactions.

Regarding the incidence of aphids (*Brevicoryne brassicae*), the organic system showed a higher susceptibility (21.84% compared to 5.26% in the conventional), which is related to the absence of synthetic inputs and a greater reliance on the natural balance of the agroecosystem, as noted by Costa et al. (2023) and Vacante and Kreiter (2017). In the conventional system, Ca was the only significant factor, whereas in the organic system, the effects of N and Ca were complex and nonlinear. This reflects a greater sensitivity of organic management to nutrient combinations, possibly associated with interactions with soil microbiota and induced defense mechanisms, as suggested Guerrieri and Digilio (2008).

Regarding plant height, both systems showed progressive growth, although the conventional system was more homogeneous (CV ≤ 1%). The organic system showed significant differences at intermediate stages (60 and 75 DAT), which could be related to a more gradual release of nutrients and lower immediate availability. According to Marschner (2012), nitrogen is a key nutrient in cellular elongation and the formation of vegetative tissues, although excess can negatively affect flowering (Mainardi Fazio, 2017). These observations were consistent with what was reported by Rodríguez-González et al. (2020) about the influence of microclimatic factors on the structural development of plants.

In terms of inflorescence performance, the most pronounced difference was observed in the average weight per unit, which was higher in the conventional system (up to 750 g). Although both systems produced the same amount of inflorescences per hectare, the conventional system accumulated more biomass, possibly due to more efficient nutrient absorption and lower physiological stress. This aligns with what Puenayan et al. (2008) and Cartagena Ayala (2014) indicated, who state that the response of broccoli to nitrogen fertilization is highly dependent on the synchronization with the crop cycle.

Overall, the results suggest that while the conventional system allows for greater control and homogeneity in performance and crop health, the organic system requires more careful and adaptive management of nutrients. Furthermore, the interactive and quadratic effects found in the organic system underscore the need for more specific research on the optimal balance of nutrients in agroecological systems. In line with what was noted by Rahman (2022), plant nutrition should be considered not only as a productive tool but also as a component of integrated management that influences plant-pest relationships and the sustainability of the agricultural system.

4. Conclusions

The statistical analysis, using ANOVA and regression models, allowed for the identification of differentiated patterns in the dynamics of the pest and in crop behavior according to the type of fertilization. Regarding the incidence of aphids, the conventional system recorded a lower average level (5.26%) and lower variability (CV = 1.91%), compared to the organic system (21.84%, CV = 4.00%), which indicates greater phytosanitary stability under conventional management. These results could be associated with the influence of nutritional management on plant resistance and the lower use of agrochemicals in organic systems.

The regression analysis indicated that Ca had a significant and negative impact on the incidence of aphids in both systems, especially in the conventional one (R^2 = -0.480), which confirms its key role in strengthening plant tissues and the structural resistance of plants. In the organic system, its reducing effect was also evident, although less pronounced (R^2 = -0.1826). For its part, N showed a more complex effect. While high doses initially increased incidence, possibly due to the stimulation of young tissues more susceptible to attack, balanced combinations with Ca tended to decrease the presence of aphids. Moreover, the quadratic and interactive effects (N^2, Ca^2, and N·Ca) were statistically significant mainly in the organic system, which shows a more sensitive and nonlinear response of the pest to nutritional variations.

Ca was the factor with the greatest influence in most of the fitted models. In the conventional system, it had a negative and significant effect on flower production and on aphid incidence, suggesting that high doses limit yield but contribute to reducing pest pressure. In the organic system, the negative effect of Ca was also evident, although less pronounced. N, on the other hand, showed a slight negative effect on production in both systems, with no significant results in most models. This indicates that its excess does not improve yield and even increases susceptibility to pests. However, its effect on aphid incidence was slightly reduced when balanced with Ca.

In the fitted models, quadratic interactions and cross interactions (AA, BB, AB) were more relevant in the organic system, reflecting a greater sensitivity to nutrient combinations. This highlights the need for more precise nutritional management in organic systems, where small changes in dosage generate nonlinear responses.

In summary, the conventional system was more efficient in terms of performance and pest control, with more consistent and predictable responses. However, the organic system showed agronomically interesting behavior, with potential for improvement through fine-tuning of N and Ca doses. Therefore, balanced and strategic management of these nutrients, tailored to each production system, is key to optimizing the health and productivity of the broccoli crop.

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Contributor roles

- Roberto Alexander Taco Guamán: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, writing—original draft, writing—review & editing.

Ethical implications

Ethics approval not applicable.

Conflict 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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