https://doi.org/10.1590/1678-4499.20240039

Nutritional phosphorus recommendation for garlic cultivars grown in subtropical climate

Leandro Hahn[1], Anderson Luiz Feltrim[1], Marcos Mattos Ender[1], Douglas Luiz Grando[2,*], Jean Michel Moura-Bueno[2], Lincon Oliveira Stefanello[3], Carina Marchezan[2], Gustavo Brunetto[2]

1. Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina – Caçador (SC), Brazil.
2. Universidade Federal de Santa Maria – Departamento de Solos – Santa Maria (RS), Brazil.
3. Universidade Tecnológica Federal do Paraná – Santa Helena (PR), Brazil.

Received: Feb. 8, 2024 | **Accepted:** May 28, 2024

Section Editor: Osvaldo Guedes Filho

***Corresponding author:** douglas.agn@hotmail.com

How to cite: Hahn, L., Feltrim, A. L., Ender, M. M., Grando, D. L., Moura-Bueno, J. M., Stefanello, L. O., Marchezan, C. and Brunetto, G. (2024). Nutritional phosphorus recommendation for garlic cultivars grown in subtropical climate, Bragantia, 83, e20240039. https://doi.org/10.1590/1678-4499.20240039

ABSTRACT: The study aimed to propose critical levels (CL) and sufficiency ranges of phosphorus (P) in leaves and soil, and rates of maximum technical (MTE) and economic (MEE) efficiency, to maximize marketable bulb yield in garlic (*Allium sativum*) cultivars grown in a subtropical climate. Field experiments were conducted for two seasons on clay soils in southern Brazil. The cultivars 'Chonan', 'Ito', and 'Roxo Caxiense' were subjected to the application of P rates (0, 50, 100, 250, and 500 kg $P_2O_5 \cdot ha^{-1} \cdot yr^{-1}$). Garlic yield, soil P concentrations (Mehlich-1), and total P in leaves were determined. The CL in relation to total yield garlic yield were 3.5, 4.5, and 3.4 g $P \cdot kg^{-1}$ in leaves and 18, 28, and 14 mg $P \cdot dm^{-3}$ in soil, for 'Chonan', 'Ito', and 'Roxo Caxiense', respectively. The CL in relation to marketable garlic yield were 4.0, 3.5, and 3.6 g $P \cdot kg^{-1}$ in leaves and 22, 26, and 13 mg $P \cdot dm^{-3}$ in soil, for the respective cultivars. The MTE rates were 397 and 336 kg $P_2O_5 \cdot ha^{-1}$, and the MEE rates were 353 and 297 kg $P_2O_5 \cdot ha^{-1}$, for total and marketable garlic bulb yield. Based on our results, we recommend that garlic growers use when possible the individual nutritional reference values for specific garlic cultivars.

Key words: P fertilization; leaf analysis; nutritional diagnosis methods; P efficiency use; machine learning.

INTRODUCTION

Garlic (*Allium sativum*) is grown on approximately 1.63 million hectares worldwide, in traditional producing countries such as China and India (FAOSTAT 2021). In Latin America, Brazil is the second largest garlic producer with 12.2 thousand hectares cultivated, where 155.7 thousand tons of bulbs are produced annually (IBGE 2020). However, Brazil is still the world's second largest importer of garlic; the first one is Indonesia (FAOSTAT 2021). This importation arises because production in Brazil does not fulfill its demand, and this deficit in production can be attributed to various factors, including the acidity and inherently low fertility of the soils in Brazil and other Latin American countries (Carneiro et al. 2016, Sebnie et al. 2018). In addition, in subtropical climate zones, critical issues and challenges such as climate conditions (Joshi et al. 2023), water availability (Rodríguez et al. 2023), and soil nutrient deficiency (Althaus et al. 2018) negatively affect crops yield and quality (El-Metwally et al. 2022, Shaaban et al. 2023). Therefore, these soils do not adequately supply the plants need for phosphorus (P). Thus, to increase the availability of P to garlic plants, phosphate fertilization is necessary (Cunha et al. 2016, Santos et al. 2017).

P availability and uptake are dramatically influence by edaphic conditions, such as soil pH (Barrow and Debnath 2015, Penn and Camberato 2019), mineral composition (Li et al. 2021), altitude, and temperature (Oliveira et al. 2020). Therefore, in addition to artificial P supply, several tactics should be done to enhance P use efficiency and utilization (Saudy et al. 2020, Shaaban et al. 2023).

In garlic cropping system, P can be applied on soils and incorporated at depth, normally 0–20-cm layer (Santos et al. 2017, Oliveira Neto et al. 2020). However, in highly weathered soils, such as clayey soils, much of the applied P is rapidly adsorbed (Almeida et al. 2018, Boitt et al. 2018), especially, on functional groups of inorganic reactive soil particles, such as 2:1, 1:1 clay minerals, hydroxides, oxides, and oxyhydroxides of iron (Fe), aluminum (Al), and manganese (Mn) (Alovisi et al. 2020, Oliveira et al. 2020). Thus, a small portion of the applied P will be made available to garlic plants to contribute to growth and yield (Shen et al. 2011). However, virus-free garlic cultivars may possess different mechanisms/strategies for nutrient uptake, transport and accumulation, which may generate higher bulb yield (Marodin et al. 2019). Also, garlic cultivars may possess distinct yields and, consequently, different demands for nutrients, as P (Resende et al. 2013, Sebnie et al. 2018).

Thus, it is necessary to propose the critical levels (CL) and sufficiency ranges (SR) of nutrients in garlic cultivars, to initially establish the real demand of P application (Cunha et al. 2016, Lima Neto et al. 2020). CL and SR can be established from soil and tissue analysis results, which are related to variables of interest, such as marketable bulb yield (Cunha et al. 2016), or quality variables, such as bulb diameter classes (Triharyanto et al. 2021). To develop the CL and SR estimation models, the yield variables are converted into relative yield (%) considering each cultivar, fertility ranges and harvest. The models are developed using plateau regression to quantify the relationship between the dependent variables (total and marketable yield) with the concentration of nutrients in the soil and leaves (Stefanello et al. 2023). The critical concentration is assumed to be the point at which the fitted line reaches the plateau, demonstrating no further increase in yield as the nutrient concentration increases. The analysis will be carried out, assuming a 90% confidence interval, to determine the threshold concentrations (SR) and the highest density of nutrient occurrence (CL). Also, maximum technical efficiency (MTE) and maximum economic efficiency (MEE) rates of P may be proposed to obtain maximum total and marketable bulb yield, according to what is most profitable to the farmer. These propositions can be carried out at regional level, but also at cultivar level (Wu et al. 2016, Bessa et al. 2020), contributing to the rationalization of the use of phosphate fertilizers.

CL and SR in leaves and soils, and MTE and MEE rates of nutrients, could be determined from advanced mathematical models, such as those obtained using techniques involving *machine learning* and Bayesian modeling. This approach has been used to provide technical support in developing criteria for decision making on the real need for fertilizer in recommendation systems (Kyveryga et al. 2013). However, studies addressing the joint employment of these techniques in the estimation of CL and SR of nutrients in soils and leaves are still scarce in the world (Ciampitti et al. 2021), especially based on good sets of experiments conducted in various locations.

Choosing the appropriate crop cultivar is a significant practice to be adapted to different harsh conditions (Saudy et al. 2020, Shahin et al. 2023). Due to the variation in cultivars potential to exploit soil, the nutrient use efficiency differed (Noureldin et al. 2013, Chen et al. 2023). The definition of CL, SR and rates of MTE and MEE may contribute to increasing the yield and quality of garlic. However, it will enable farmers to choose materials more efficient in the use of P, without reducing yield. Also, it encourages the sustainable use of phosphate fertilizers, which have finite reserves (Vaccari et al. 2019). The sum of these strategies will favor the increase of P utilization efficiency and decrease the potential for soil and wastewater contamination by excess P (Baker et al. 2015, Fan et al. 2021). The study aimed to propose CL and SR of P in leaves and soil, and rates of MTE and MEE, to maximize marketable bulb yield in different garlic cultivars grown in subtropical climate.

MATERIAL AND METHODS

Experimental setup

There were 12 trials in 2015 and six trials in 2016 conducted in Fraiburgo, Frei Rogério, and Curitibanos cities, Santa Catarina state, south of Brazil (Fig. 1). The soils were clayey and classified as Ultisols (Soil Survey Staff 2014). The landscape was moderately flat to slightly undulated. Edaphic, climatic, and managerial data was collected in Fraiburgo, Santa Catarina, Brazil (27°04'50.4"S, 50°54'16.4"W, elevation 1,041 m).

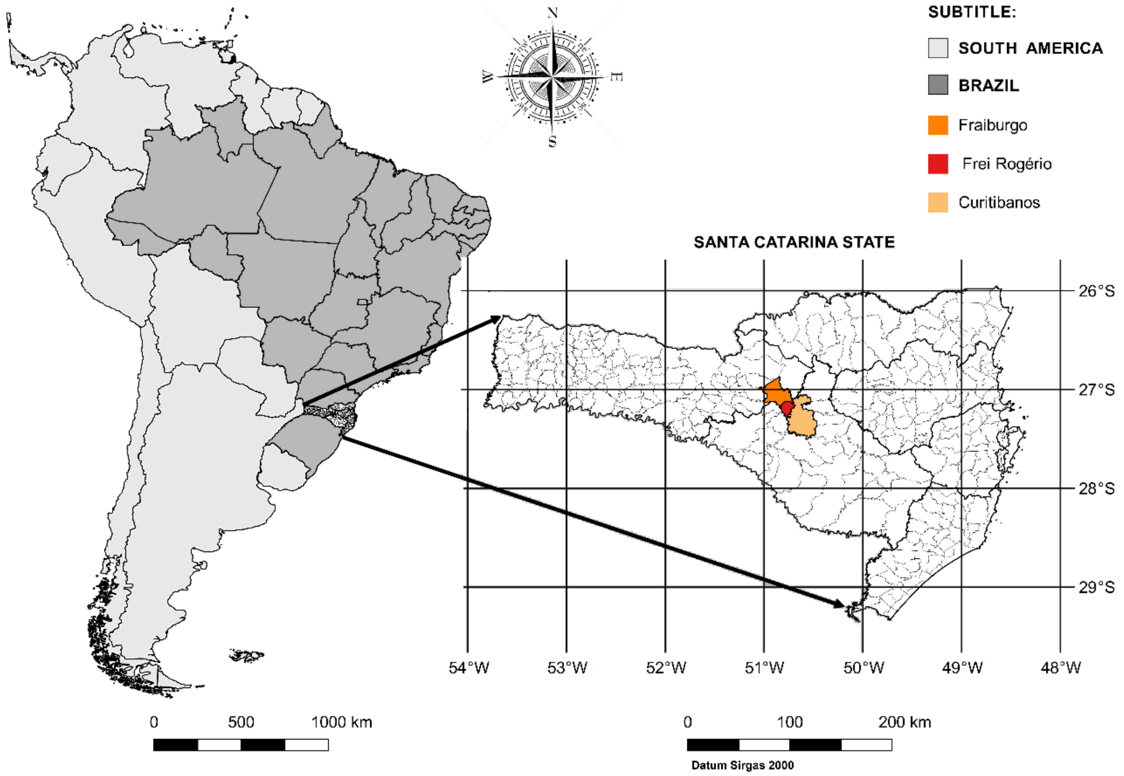

Figure 1. The geographic location of the Fraiburgo, Frei Rogério, and Curitibanos municipalities, Santa Catarina state, south of Brazil, where field experiments with phosphate fertilization and garlic cultivars were conducted.

The region's climate was classified as Cfb according to the Köppen's system, which is temperate and humid with mild summers (Alvares et al. 2013). The crops were sprinkler-irrigated at need. Climatic data observed during the field experiments were collected by automated meteorological stations (Hahn et al. 2024).

The plots consisted of three double-line planting beds, 5 m in length (Hahn et al. 2020). The seeds were obtained from virus-free meristem culture of the cultivar noble groups 'Chonan', and 'Ito', and the 'Roxo Caxiense' was the conventional cultivar (Table 1), which has the greatest potential for yield improvement in Brazil. Those late cultivars have purple bulbs and require long days for bulb formation (Resende et al. 2013, Hahn et al. 2022). Seed cloves were vernalized at 2–5 °C for 20–30 days before planting. Planting density was 45 seed cloves$\cdot$m^{-2}. Preceding crops were maize (*Zea mays*), soybean (*Glycine max*), common bean (*Phaseolus vulgaris*), or fallow. The other cultural practices were those recommended in the marketable fields of the region.

The experimental design used in every experiment was completely randomized blocks with three replications. The experimental stands received five P rates (0, 50, 100, 250, and 500 kg $P_2O_5\cdot ha^{-1}\cdot yr^{-1}$) using triple superphosphate (TSP) as the P source (42% P_2O_5). In all treatments, the rate of 300 kg $N\cdot ha^{-1}$: 1/3 was applied top-dressed at planting; 1/3 top-dressed 30 days after planting; and 1/3 was top-dressed at bulb initiation (approximately 95 days after planting, when plants differentiated into bulbs). The equal rate of 400 kg $K_2O\cdot ha^{-1}$ and 100 kg $N\cdot ha^{-1}$ was applied broadcast before planting. The respectively NPK rates were applied in the total area, and the soil was turned by rotary tiller in the 0–20-cm layer. Plantation dates across sites and years varied between June 1st and July 26th. The harvesting dates varied between November 3th and December 8th, with 144 average cycle days (Table 1).

Table 1. Field location, garlic cultivar, planting date, cycle, and physical and chemical soil attributes before experiment start and fertilizer application in Southern Brazil.

Soil	City	Garlic cultivar	Planting date	Cycle	Clay	OM	pH in water	P	K	Ca	Mg	CEC	V	P availability classes*
				days	----- % -----			mg·dm^{-3}		---- cmol$_c$·dm^{-3} ----			%	
1	Curitibanos	Ito	07/03/2015	174	63	2.9	5.9	17.2	207.4	7.4	2.5	13.9	75.0	High
2	Fraiburgo	Chonan	07/14/2015	119	60	4.5	6.0	49.7	518.4	9.2	2.2	15.5	74.4	Very high
3	Curitibanos	Roxo Caxiense	07/23/2015	132	62	3.3	6.1	14.2	315.4	6.0	3.3	13.6	83.1	Medium
4	Curitibanos	Ito	07/26/2015	135	41	3.4	6.1	12.8	132.0	9.1	4.4	16.7	67.8	Low
5	Fraiburgo	Ito	06/01/2015	155	62	4.3	5.7	11.5	116.6	6.9	2.0	13.6	75.1	Medium
6	Fraiburgo	Ito	06/29/2015	142	59	4.0	6.7	34.9	108.0	12.7	1.1	16.0	87.8	High
7	Fraiburgo	Chonan	06/02/2015	154	58	4.9	5.4	13.3	237.6	6.1	2.0	15.6	85.6	Low
8	Fraiburgo	Chonan	06/28/2015	162	61	3.6	6.3	19.0	298.1	8.5	2.3	13.5	84.2	High
9	Frei Rogério	Chonan	06/20/2015	143	63	3.9	5.8	11.5	138.2	6.1	2.6	13.9	80.7	Medium
10	Fraiburgo	Ito	07/01/2015	145	58	4.1	5.9	17.4	261.0	8.2	3.4	19.3	67.8	Medium
11	Fraiburgo	Ito	06/01/2015	155	60	4.7	6.2	5.7	250.6	7.8	3.0	14.5	84.6	Low
12	Frei Rogério	Ito	06/20/2015	139	66	3.1	6.5	17.0	173.9	6.5	3.3	12.8	82.4	High
1	Curitibanos	Ito	07/05/2016	141	63	nd	nd	23.7	nd	nd	nd	nd	nd	High
3	Curitibanos	Roxo Caxiense	07/22/2016	133	62	nd	nd	12.3	nd	nd	nd	nd	nd	Medium
4	Curitibanos	Ito	07/27/2016	126	41	nd	nd	7.9	nd	nd	nd	nd	nd	Low
8	Fraiburgo	Chonan	06/02/2016	154	61	nd	nd	9.3	nd	nd	nd	nd	nd	Low
9	Frei Rogério	Chonan	06/15/2016	156	63	nd	nd	4.4	nd	nd	nd	nd	nd	Very low
12	Frei Rogério	Ito	06/14/2016	149	66	nd	nd	18.2	nd	nd	nd	nd	nd	High

OM: organic matter; pH in water (1:1); P and K were extracted by Mehlich-1; Ca and Mg were extracted by KCl 1 M; CEC: cation exchange capacity at pH 7 (Ca^{2+} + Mg^{2+} + K^+ + (H+Al)); V%: Ca-Mg-K saturation; nd: not determined; the seeds of Ito and Chonan garlic cultivars were obtained from virus-free meristem culture; *according to CQFS-RS/SC (2004).

Tissue analysis

Ten complete young leaves (fourth fully expanded) were collected in each plot at the beginning of clove differentiation (Hahn et al. 2020). The leaves were washed with distilled water, dried at 65 ± 5 °C in an oven with forced air circulation until reaching constant weight. Afterwards, the leaves were ground in a Willey-type mill (Tecnal, R-TE-650/1, Brazil) and passed through a 1-mm mesh sieve. A part of the leaf tissues was submitted to nitro perchloric digestion to determine the concentration of other nutrients (Embrapa 2009). The P concentration was determined at 882 nm in a ultraviolet–visible spectrophotometer (Bell Photonics, 1,105, Brazil) (Murphy and Riley 1962).

Soil analysis

The initial soil characterization before fertilizer application and garlic planting is presented in Table 1. Eight soil samples per plot were collected in the 0–20-cm surface layer 15 to 20 days after fertilizer rates application and garlic planting. Also, at the harvest time soil was again analyzed. The soils were air-dried and ground to 2-mm mesh before conducting physical-chemical analysis. The clay content was determined by the densimeter method (Donagema et al. 2011). The pH was determined in water (1:1 soil-to-water volumetric ratio). The available P and K were extracted by Mehlich-1, and exchangeable Ca and Mg were extracted by KCl 1 mol·L^{-1} (Tedesco et al. 1995). The available P in the soil was determined at 882 nm in a ultraviolet–visible spectrophotometer (Bell Photonics, 1,105, Brasil) (Murphy and Riley 1962). The exchangeable K, Ca and Mg in the soil was determined in an atomic absorption spectrophotometer (PerkinElmer, AA200, Norwalk, United States of America). Cation exchange capacity was determined as the sum of exchangeable cations and total acidity (SMP buffer pH) (Tedesco et al. 1995). The organic carbon content of the soil was determined by wet oxidation in a sulphochromic solution–$K_2Cr_2O_7$ + H_2SO_4 (Walkley and Black 1934), followed by multiplication of the 1.724 constant to obtain soil organic matter content (Silva et al. 2009).

Garlic yield and bulb classification

The bulbs were collected in uniform 1-m-long rows made of three double plant lines per plot (Hahn et al. 2020). The bulbs were weighed after 40 days of natural drying. Marketable bulbs were classified according to its diameter at #2 (< 32 mm ∅), #3 (32–37 mm ∅), #4 (37–42 mm ∅), #5 (42–47 mm ∅), #6 (47–56 mm ∅), and #7 (> 56 mm ∅), according to Luengo et al. (1999). Bulbs showing secondary growth or damage were considered non-marketable. The average of the two years of evaluation were used to calculate yield and garlic classes. For annual yield, the average bulb yield of all cultivars for the respective crops was used.

Statistical analysis and critical levels and sufficiency ranges estimation of nutrients

The total yield data were submitted to a conditional inference regression analysis to highlight which of the factors (cultivar and P rate) had greater importance in conditioning the differences on total yield. Subsequently, the response variables (total and marketable yield) were submitted to analysis of variance (ANOVA). The factors 'cultivar' and 'rates of P', as well as their interaction, were considered fixed effect, and the effects of blocks were nested in crops (random effect). The normality of the residuals was tested by means of the Shapiro-Wilk's test and, as they did not meet the normality assumption, they were compared by the Friedman's test, with error probability of 5% ($p < 0.05$). The data were also subjected to Pearson's correlation. All analyses were performed in the R statistical environment (R Core Team 2021), using the packages "*agricolae*" (Mendiburu 2021) and "*Rmisc*" (Hope 2013), for descriptive statistical analysis, and "*ggplot2*" (Wickham et al. 2021), for graphing.

For the development of models to estimate CL and SR, the total and marketable bulb yield was converted into relative yield (%) considering cultivars, crop seasons, and experiments. The models were developed through regression with plateau to quantify the relationship between the dependent variables (yield), with the concentration of P in the soil at planting (after P application) and leaves at the beginning of clove differentiation. Hierarchical Bayesian analysis was used to fit the regression models. In this step, a Monte Carlo simulation with Markov chains (Gelman and Hill 2007) was performed using the *Gibbs sampling* algorithm with 20,000 random drawings after a heating period of 10,000 interactions. The sampling step was performed according to a normal distribution based on the a posteriori distribution of nutrient concentrations. The modeling was implemented using the '*rjags*' package (Plummer 2016) in the R statistical environment (R Core Team 2021). The critical concentration was assumed to be the point at which the fitted line reaches the plateau, showing no further increase in yield as the P concentration increases. Finally, a frequency density analysis, assuming a 90% confidence interval, was performed to determine the SRs, and the highest CL density.

Maximum technical efficiency and maximum economic efficiency

The regressions for fitting the MTE and MEE of the variables of interest were performed using Eq. 1:

$$y = a \pm b_1 x \pm b_2 x^2 \tag{1}$$

Equation 2 was used for the estimation of the MTE:

$$MTE = \frac{-b_1}{2b_2} \tag{2}$$

Equation 3 was used for the estimation of the MEE:

$$MEE = \frac{\left[\left(\frac{t}{w}\right) - b_1\right]}{2b_2} \tag{3}$$

where: t: the value of the input (TSP); w: the marketable value of the product (garlic).

The average price of TSP in the years 2015 and 2016 was US\$ 1.13·kg^{-1} of P_2O_5 (Conab 2021b). The average price of a kilogram of marketable grade garlic in the years 2016 and 2017 was US\$ 2.79·kg^{-1} (Conab 2021a). The value used for the non-marketable class was 10% of the total value of the marketable class. Thus, for calculation purposes the average price of the kilogram of garlic in the years 2016 and 2017 of US\$ 1.99·kg^{-1} was used, considering the average value received by the total yield (marketable class + non-marketable class).

RESULTS

Garlic yield and bulb classification

The cultivar factor showed the greatest effect on total garlic yield (54%), in relation to P rates, in the 2015 and 2016 crop seasons (Fig. 2). The cultivar 'Roxo Caxiense' showed the highest yield. The 'Roxo Caxiense' cultivar showed subtle effect of P rates (7%), in which the highest marketable yields were observed at rates of 100, 250 and 500 kg P_2O_5·ha^{-1} (Fig. 2).

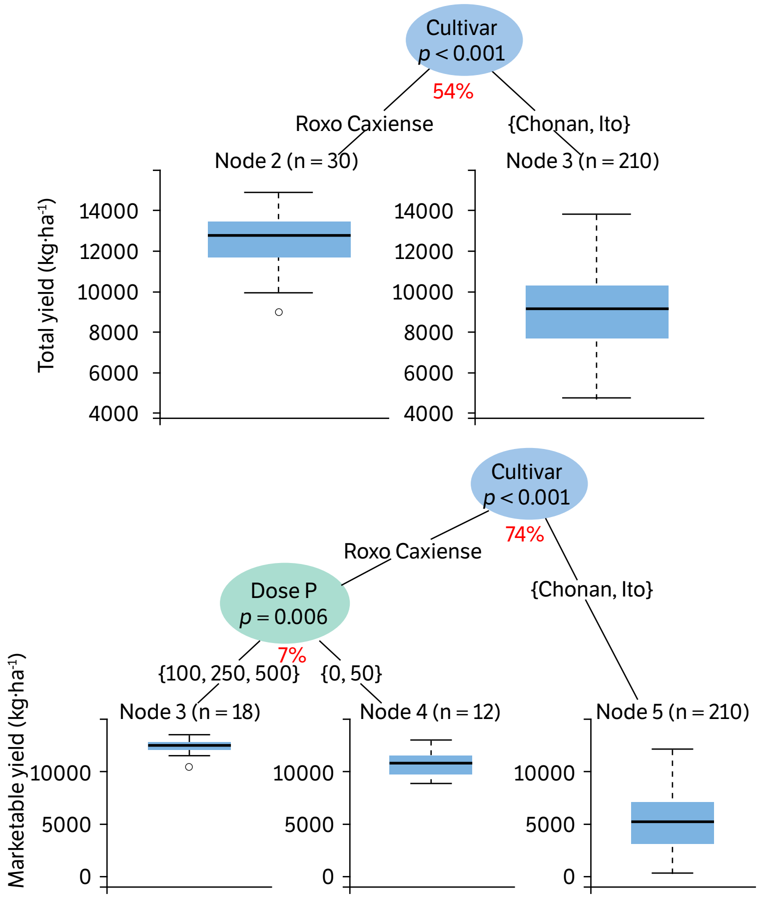

Figure 2. Conditional inference trees for total garlic yield in field experiments in the South of Brazil as affected by garlic cultivar (Cultivars) and phosphate fertilization (P rates). The number of the node indicates the sequence of the split with respective split significance (p) in the circle. Boxplots show data distribution in each terminal node. The number of observations (n) is shown. Boxplots represent the interquartile range (first and third quartiles), while vertical lines extending from the boxes indicate the upper and lower limits of the data. The line within the boxplot is the median (second quartile, 50 percentile). White dots represent outliers.

Total yield did not differ statistically ($p < 0.05$) among garlic cultivars (Fig. 3a), but yield differed statistically among crop seasons (Hahn et al. 2024). Marketable and non-marketable yields differed statistically among garlic cultivars (Figs. 3b and 3c). The cultivar 'Roxo Caxiense' showed the highest marketable yield compared to the cultivars 'Chonan' and 'Ito' at 1.4 and 1.7 time more, respectively (Fig. 3b). The cultivar 'Ito' showed the highest non-marketable yield and 'Roxo Caxiense' the lowest (Fig. 3c). This fluctuation of marketable and non-marketable yield of the cultivars was evident between the harvests (Hahn et al. 2024). In the 2016 crop season, the marketable yield was higher compared to the 2015 and, consequently, the non-marketable yield was lower (Hahn et al. 2024).

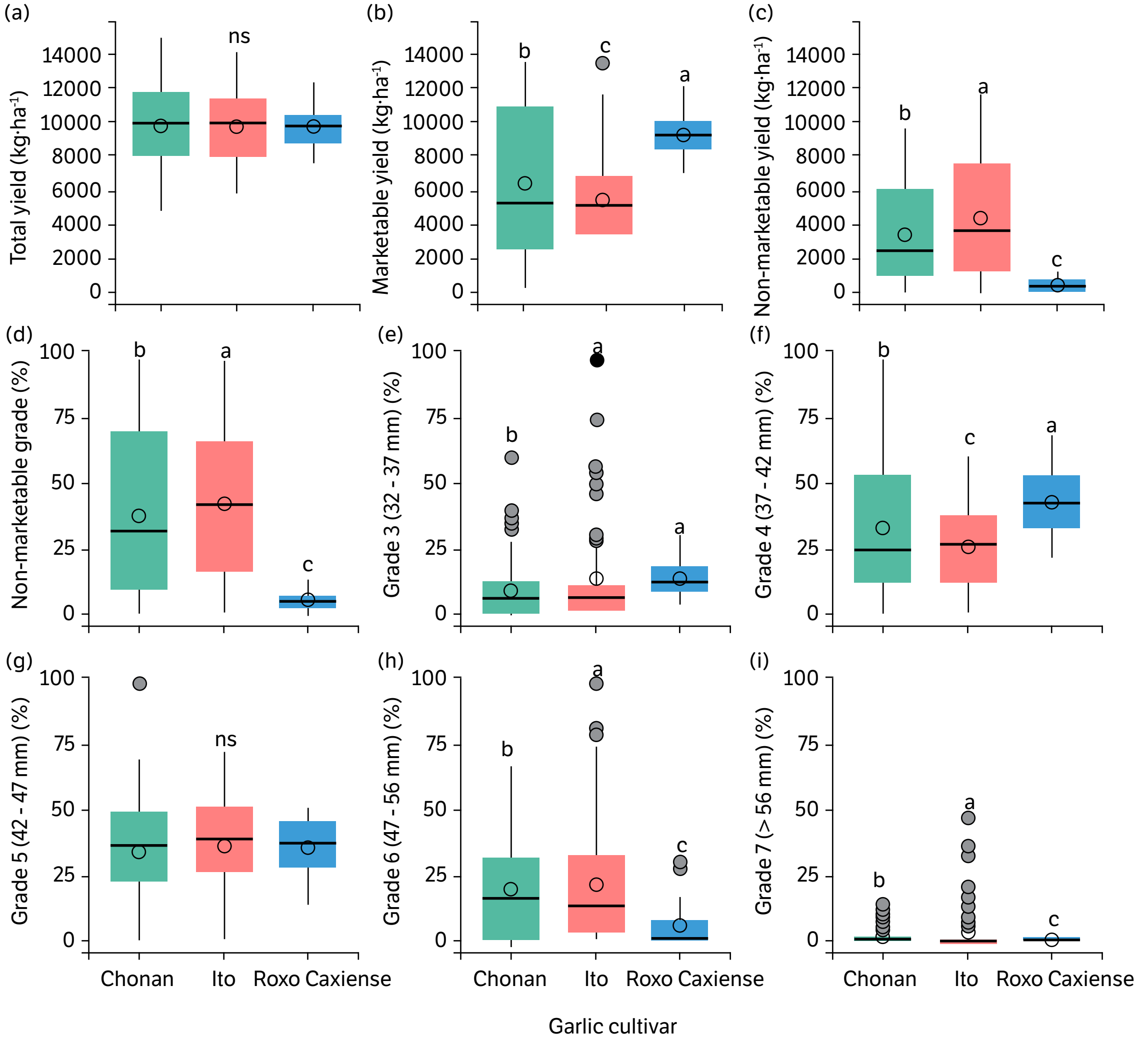

Figure 3. Garlic production evaluation according to different cultivars. (a) Total garlic yield, (b) marketable yield, (c) non-marketable yield, (d) non-marketable grade, and (e, f, g, h and i) garlic bulbs classification 3 to 7 of garlic cultivars subjected to phosphate fertilization in field experiments in the South of Brazil. Boxplots represent the interquartile range (first and third quartiles), while vertical lines extending from the boxes indicate the upper and lower limits of the data. The line within the boxplot is the median (second quartile, 50 percentile). Circle inside the boxes represent the mean. Gray dots represent outliers.

Cultivars showed differences between bulb classifications for all classes, except for class 5 (Fig. 3g). The cultivar 'Ito' showed the highest proportions in classes 3, 6 and 7 compared to the other cultivars (Figs. 3e, 3h and 3i). The cultivar 'Roxo Caxiense' showed the highest proportions in classes 3 and 4 (Figs. 3e and 3f), and the lowest in classes 6 and 7 (Figs. 3h and 3i).

Phosphorus in leaves and soil

P concentrations in leaves did not differ statistically ($p < 0.05$) between cultivars (Fig. 4a). The average P concentration in the leaves of the three cultivars was 5.2 g P·kg^{-1}. However, the highest contents of available P extracted by Mehlich-1 were observed in soils cultivated with the 'Roxo Caxiense' cultivar (Fig. 4b). The lowest available P contents were observed in soils cultivated with the 'Ito' and 'Chonan' cultivars, respectively, in 1.1 and 1.2 time related to 'Roxo Caxiense' (Fig. 4b).

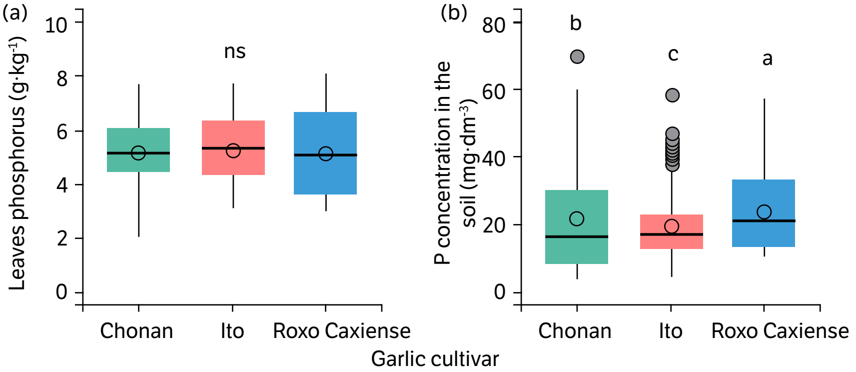

Figure 4. Phosphorus garlic nutrition according to different cultivars. (a) P concentration in garlic leaves and (b) the soil after the harvest (by Mehlich-1) of the garlic cultivars subjected to phosphate fertilization in field experiments in the South of Brazil. Boxplots represent the interquartile range (first and third quartiles), while vertical lines extending from the boxes indicate the upper and lower limits of the data. The line within the boxplot is the median (second quartile, 50 percentile). Circle inside the boxes represent the mean. Gray dots represent outliers.

Critical levels and sufficiency ranges of leaves phosphorus

The CL of P in leaves in relation to total yield were 3.5, 4.5 and 3.4 g P·kg^{-1}, respectively, for 'Chonan', 'Ito' and 'Roxo Caxiense' cultivars (Fig. 5a). The SR obtained in relation to total yield varied from 3 to 5.5 g P·kg^{-1}. The CL of P in leaves in relation to marketable yield were 4, 3.5 and 3.6 g P·kg^{-1} for 'Chonan', 'Ito' and 'Roxo Caxiense' cultivars (Fig. 5b). The SR obtained in relation to marketable yield varied from 3 to 4.8 g P·kg^{-1}.

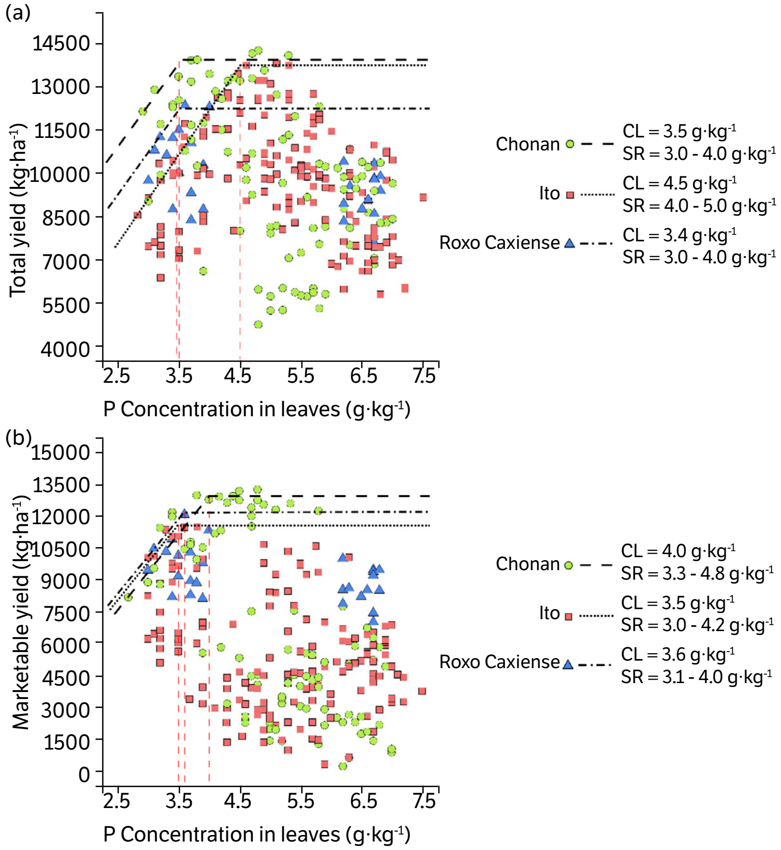

Figure 5. Critical levels (CL) and sufficiency ranges (SR) of phosphorus (P) in leaves concerning (a) total and (b) marketable yield of the garlic cultivars subjected to phosphate fertilization in field experiments in the South of Brazil.

Critical levels and sufficiency ranges of soil phosphorus

The CL of P in soil in relation to total yield were 23, 28, and 14 mg P·dm^{-3}, respectively, for 'Chonan', 'Ito' and 'Roxo Caxiense' cultivars (Fig. 6a). The SR obtained in relation to total yield varied from 10 to 35 mg P·dm^{-3}. The CL of P in soil in relation to marketable yield were 22, 26 and 13 mg P·dm^{-3}, respectively, for 'Chonan', 'Ito' and 'Roxo Caxiense' cultivars (Fig. 6b). The SR obtained in relation to total yield varied from 13 to 30 mg P·dm^{-3}.

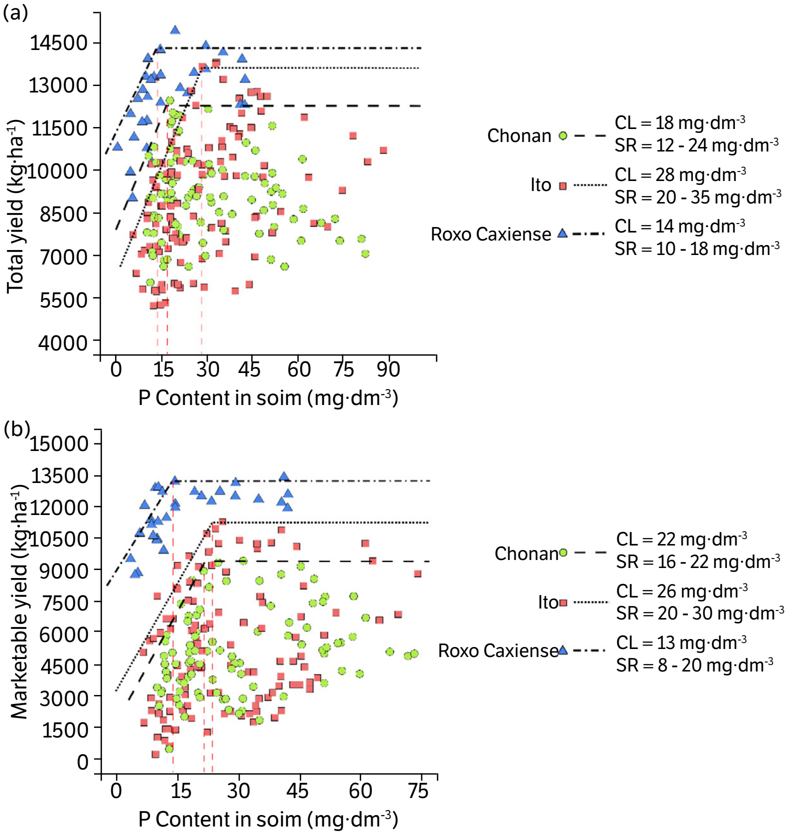

Figure 6. Critical levels (CL) and sufficiency ranges (SR) of phosphorus (P) in the soil concerning (a) total and (b) marketable yield of the garlic cultivars subjected to phosphate fertilization in field experiments in the South of Brazil.

Maximum technical efficiency and maximum economic efficiency

The MTE and MEE in relation to total garlic yield were obtained from the application of 397 and 353 kg P_2O_5·ha^{-1}, respectively (Fig. 7a). For marketable yield, the rates were 336 and 297 kg P_2O_5·ha^{-1}, for MTE and MEE (Fig. 7a). The difference in total and marketable yields, between the rates of MTE and MEE, were 44 and 37 P_2O_5·ha^{-1} (Figs. 7a and 7b). The MEE rates represented 89 and 88% of MTE rates for total and marketable yield. This reduction in fertilizer application causes the decrease of only 15 and 11 kg·ha^{-1} of total and marketable garlic yields, respectively.

DISCUSSION

The cultivar factor showed greater influence on the yield variable compared to the P rate factor (Fig. 2). This may have happened because garlic cultivars may have different kinetic parameters, as K_m, C_{min}, V_{max} and influx of nutrient uptake, in this case P (Pinto et al. 2021, Wang et al. 2021). Thus, some garlic cultivars can maintain adequate yield even in soils with lower P availability, thus becoming more efficient (Sirisena and Suriyagoda 2018, Wang et al. 2018).

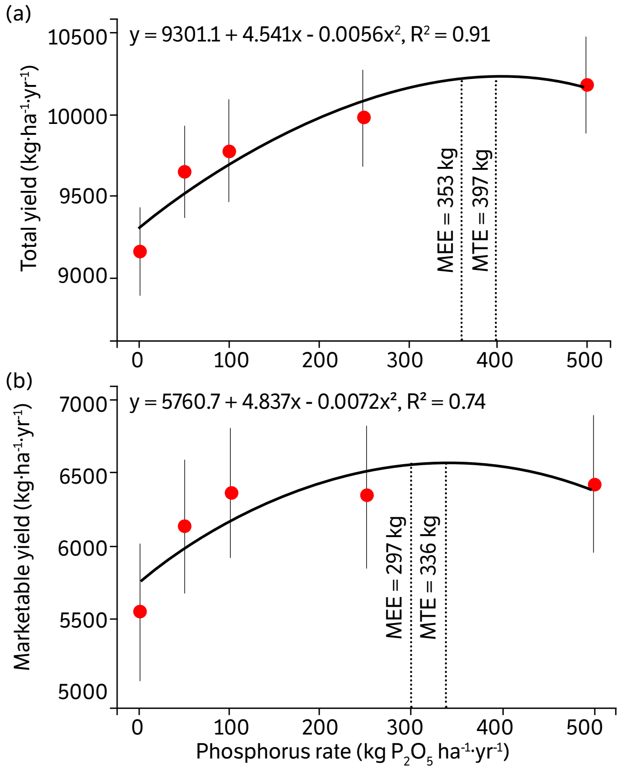

Figure 7. Rates of maximum technical efficiency and maximum economic efficiency for (a) total and (b) marketable garlic yield of the garlic cultivars subjected to phosphate fertilization in field experiments in the South of Brazil. Red dots represent the mean. Vertical lines represent the standard error of the mean.

Plants such as garlic cultivars have different specific mechanisms to increase solubility and, consequently, nutrient availability to absorption (Kulmann et al. 2020, Lambers et al. 2015). This can happen because of exudation of organic acids and pH modification in the rhizospheric soil (Sun et al. 2020, Vives-Peris et al. 2020). These strategies may increase solubilization of more recalcitrant P forms (Rahman et al. 2021), favoring the approximation of phosphate ions to the outer surface of roots, enhancing plant P uptake (Sun et al. 2020, Vives-Peris et al. 2020). Thus, in some cases, both applied P rates and available soil contents may be less important than the cultivar chosen.

The marketable yield was distinct among cultivars (Fig. 3b). This is the most important variable for garlic producers, as it represents the classes that are economically profitable. The total garlic yield did not differ statistically between the virus-free cultivars (‘Ito’ and ‘Chonan’) and the conventional one (‘Roxo Caxiense’) (Fig. 3a), representing the potential that is possible to achieve improving the nutritional management. The highest values in the non-marketable bulb class were observed in the cultivar ‘Ito’. On the other hand, the lowest value was verified in the cultivar ‘Roxo Caxiense’. Furthermore, we pointed out that the cultivar ‘Roxo Caxiense’ is planted late. Garlic in late plantings hardly overgrows in the study region, because of the shortening of the production cycle (Table 1) and because the period of plant differentiation into bubbles does not coincide with late frosts, which explains the high marketable yield (Lucini 2004). However, the ‘Roxo Caxiense’ cultivar is not cultivated on a large scale in the region of this study, because the purple color of the bulbils is not as intense as ‘Ito’ and ‘Chonan’ cultivars. Thus, this garlic is not as desired by consumers.

Most likely unfavorable weather conditions in 2015 explain the lower production of marketable garlic (4,309 kg·ha^{-1}) and higher production of non-marketable garlic (5,017 kg·ha^{-1}), compared to the 2016 crop season (9,881 and 729 kg·ha^{-1}, respectively) (Hahn et al. 2024). In 2015, negative temperatures occurred on September 12th and 13th (-1 °C), coinciding with the phase of differentiation of garlic, and high rainfall precipitation from half to the end of the production cycle of garlic (months from September to November), in which the accumulated monthly rainfall was 233, 353, and 237 mm, and the number of days of the months with rainfall was 18, 21, and 16, respectively (Hahn et al. 2024). As adverse weather conditions decreased marketable bulb yield and favored the appearance of the plant disturbance false-branching or super-sprouting, in addition to a high incidence of bacteriosis (Wu et al. 2016). These two conditions deteriorate the quality of garlic, and therefore the product is classified as non-marketable garlic.

The CL and SR of P in garlic leaves were determined individually for the three cultivars evaluated (Fig. 5). However, the average of P leaf content did not differ between these cultivars (Fig. 4a). It can be explained because plants absorb P in concentrations above physiological demands not reflecting in increasing yield. In this case, the P absorbed and diagnosed by leaf analysis were derived from fertilization and contributed to the increase in bulb yield (Nemadodzi et al. 2017, Fouda, 2020), being possible to identify the cultivar with higher P use efficiency ('Roxo Caxiense'). Also, the CL proposed in the present study are lower than the CL considered as adequate by Cunha et al. (2016) 5.2 g P·kg^{-1}, in tropical climate soil of Brazil. There are propositions of different reference values of P in garlic leaves in the literature, which may be associated with distinct factors such as climate, soil type and cultivars (Tyler et al. 1988, Castellanos et al. 2001). However, the use of regionalized values obtained in our study may contribute to greater accuracy of interpretations and recommendations. Also, the use of the most efficient garlic cultivar and adequate nutrition minimize the excess of P in soil useless to the plant (Saudy et al. 2020).

The different CL may also have occurred due to the mathematical modeling applied, adjustment coefficients chosen, or even the sum of these factors (Yu and Moyeed 2001, Liang et al. 2021). In any case, the proposed CL indicates how far human intervention of fertilization will enable returns in garlic bulb yield. In this case, garlic crops with P concentration above of SR have low probability of positive yield return with phosphate fertilizer application. We did not observe a correlation between P in the soil and P in the garlic leaves either (Hahn et al. 2024), which corroborates to the reduction of excess of soil P. Moreover, with calibrated CL the probability of nutritional imbalance is lower, resulting in a lower fertilization rate and reduction in production costs (Sucunza et al. 2018). Thus, in addition to benefits for the garlic production chain, there will be less potential for surface water contamination adjacent to garlic-grown areas (Fischer et al. 2018, Fan et al. 2021), especially in areas that have higher clay content and slope (Grando et al. 2021).

The CL and SR to garlic cultivars in the soil were identified (Fig. 6). This proposition reinforces the relationship between soil P content and garlic yield (Diriba-Shiferaw et al. 2013, Santos et al. 2017), which is not always observed in crops with incipient root system development, case of garlic (Lawande et al. 2009). Thus, to increase garlic bulb yield, it is necessary to raise the soil P content and achieve at minimum the SR (Mehlich-1). However, at contents higher than this CL, the probability of yield increment is very low (Fouda 2020, Wang et al. 2022). The soil P CL obtained in the present study for 'Roxo Caxiense' cultivar is very close to the 15 mg P·dm^{-3} proposed by the regional fertilizer recommendation system (CQFS-RS/SC 2016), for crops such as garlic (*Allium sativum*), beet (*Beta vulgaris*), carrot (*Daucus carota*), potato (*Solanum tuberosum*), and cut rose (*Rosa* spp.), grown in soils with clay contents above 60%. However, the nutritional requirement for 'Chonan' and 'Ito' cultivars were higher than the regional fertilizer recommendation system, in 1.5 and 1.7 time. Thus, with our results, it is possible to increase the nutritional recommendation system and garlic quality.

The MEE rates were obtained for total and marketable yield (Fig. 7) and provided savings of 11 and 12% in fertilizer compared to the MTE rates, respectively, although they also provided increases of 9 and 11% in yield over the control. The MTE rate for maintenance fertilization according to the regional recommendation is 300 kg P_2O_5·ha^{-1} (CQFS-RS/SC 2016), when P contents are classified as high (clay content > 60%) (CQFS-RS/SC 2016). This value is lower than the MTE rate observed in the present study, which was 397 kg P_2O_5·ha^{-1}. Thus, possibly the currently recommended MTE rate of phosphate fertilizer is being underestimated, which may be limiting the potential garlic yield (Assefa et al. 2015, Diriba-Shiferaw et al. 2013). However, we emphasize that an alternative is to use MEE, as yield gains tend to be low. Despite we are showing MTE and MEE rates of P fertilizer, we reinforce the importance of soil analysis annually to adequate phosphate rates and P levels in the soil.

With our results, the garlic recommendation system could be updated to subtropical region of Brazil. Also, it was able to identify that different cultivars demand physiologically distinct values of CL an SR. With that, it is important to make studies to improve the nutrition status for nutrients, species, regions, and climatic conditions.

CONCLUSION

The CL of P in relation to total and marketable yield in leaves and soil, for 'Chonan', 'Ito', and 'Roxo Caxiense', were proposed to garlic cultivated in a subtropical climate. The CL in relation to total yield garlic yield were 3.5, 4.5, and 3.4 g $P{\cdot}kg^{-1}$ in leaves and 18, 28, and 14 mg $P{\cdot}dm^{-3}$ in soil, for 'Chonan', 'Ito', and 'Roxo Caxiense', respectively. The CL in relation to marketable garlic yield were 4, 3.5, and 3.6 g $P{\cdot}kg^{-1}$ in leaves and 22, 26, and 13 mg $P{\cdot}dm^{-3}$ in soil, for the respective cultivars. Also, the MTE rates were 397 and 336 kg $P_2O_5{\cdot}ha^{-1}$, and the MEE rates were 353 and 297 kg $P_2O_5{\cdot}ha^{-1}$, respectively, for total and marketable garlic bulb yield.

The results from this study could help garlic growers decide on the best nutritional management, once up time that the P reference values are proposed for individual garlic cultivars improving the efficiency of the recommendations that are scarce in the literature. In addition, the soil P levels need to be constantly monitored to not achieve and cause environmental problems. However, future research is needed to improve garlic fertilization including additional macro and micronutrients.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Feltrim, A. L. and Hahn, L.; **Project administration:** Hahn, L.; **Funding Acquisition:** Hahn, L.; **Investigation:** Feltrim, A. L., Ender, M. M. and Hahn, L.; **Methodology:** Hahn, L.; **Visualization:** Grando, D. L. and Hahn, L.; **Formal Analysis:** Feltrim, A. L., Ender, M. M., Grando, D. L., Moura-Bueno, J. M. and Hahn, L.; **Writing – Original Draft Preparation:** Grando, D. L., Moura-Bueno, J. M., Marchezan, C., Brunetto, G. and Hahn, L.; **Writing – Review & Editing:** Grando, D. L., Moura-Bueno, J. M., Stefanello, L. O., Brunetto, G. and Hahn, L.; **Final approval:** Grando, D. L.

DATA AVAILABILITY STATEMENT

Suplementary data supporting the findings of this study are available in https://doi.org/10.6084/m9.figshare.26388250.v1.

FUNDING

Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina
Grant No.: 6312106

ACKNOWLEDGMENTS

Not applicable.

REFERENCES

Almeida, J. A., Correa, J. and Schmitt, C. (2018). Clay mineralogy of basaltic Hillsides in the western state of Santa Catarina. Revista Brasileira de Ciência do Solo, 42, e0170086. https://doi.org/10.1590/18069657rbcs20170086

Alovisi, A. M. T., Cassol, C. J., Nascimento, J. S., Soares, N. B., da Silva Junior, I. R., da Silva, R. S. and da Silva, J. A. M. (2020). Soil factors affecting phosphorus adsorption in soils of the Cerrado, Brazil. Geoderma Regional, 22, e00298. https://doi.org/10.1016/j.geodrs.2020.e00298

Althaus, D., Gianello, C., Tedesco, M. J., Da Silva, K. J., Bissani, C. A. and Felisberto, R. (2018). Natural fertility and metals contents in soils of Rio Grande do Sul (Brazil). Revista Brasileira de Ciência do Solo, 42, 1-15. https://doi.org/10.1590/18069657rbcs20160418

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M. and Sparovek, G. (2013). Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Assefa, A. G., Misgina, S. H. and Abrha, Y. W. (2015). Effect of inorganic and organic fertilizers on the growth and yield of garlic crop (*Allium sativum* L.) in Northern Ethiopia. Journal of Agricultural Science, 7, 80-86. https://doi.org/10.5539/jas.v7n4p80

Baker, A., Ceasar, S. A., Palmer, A. J., Paterson, J. B., Qi, W., Muench, S. P. and Baldwin, S. A. (2015). Replace, reuse, recycle: Improving the sustainable use of phosphorus by plants. Journal of Experimental Botany, 66, 3523-3540. https://doi.org/10.1093/jxb/erv210

Barrow, N. J. and Debnath, A. (2015). Effect of phosphate status and pH on sulphate sorption and desorption. European Journal of Soil Science, 66, 286-297. https://doi.org/10.1111/ejss.12223

Bessa, A. T. M., Negreiros, M. Z. de, Lopes, W. D. A. R., Paiva, L. G. and Silva, O. M. D. P. (2020). Quality of virus-free garlic grown under high altitude conditions in the semiarid region of the northeast of Brazil. Revista Caatinga, 33, 945-953. https://doi.org/10.1590/1983-21252020v33n409rc

Boitt, G., Schmitt, D. E., Gatiboni, L. C., Wakelin, S. A., Black, A., Sacomori, W., Cassol, P. C. and Condron, L. M. (2018). Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil. Geoderma, 321, 164-172. https://doi.org/10.1016/j.geoderma.2018.02.010

Carneiro, J. S. da S., Faria, Á. J., De, G., Fidelis, R. R., Silva Neto, S. P. da, Santos, A. C. and Silva, R. R. (2016). Diagnosis and management of spatial variability of soil fertility in the Cerrado. Scientia Agraria, 17, 38-49. https://doi.org/10.5380/rsa.v17i3.50096

Castellanos, J. Z., Ojodeagua, J. L., Mendez, F., Villalobos-Reyes, S., Badillo, V., Vargas, P. and Lazcano-Ferrat, I. (2001). Phosphorus requirements by garlic under fertigation. Better Crops With Plant Food, 15, 21-23. Available in: http://www.ipni.net/publication/bci.nsf/0/5501B24F264B9BAB85257BBA006868B7/$FILE/Better%20Crops%20International%202001-2%20p21.pdf

Chen, B., Feng, L., Gu, H., Zhang, M., Chai, Z. and Feng, G. (2023). Critical shoot phosphorus concentrations for changes in root morphology to improve phosphorus uptake in cotton. Journal Plant Nutrition Soil Science, 186, 130-140. https://doi.org/10.1002/jpln.202200115

Ciampitti, I. A., Fernandez, J., Tamagno S., Zhao, B., Lemaire, G. and Makowski, D. (2021). Does the critical N dilution curve for maize crop vary across genotype x environment x management scenarios? – a Bayesian analysis. European Journal of Agronomy, 123, 126202. https://doi.org/10.1016/j.eja.2020.126202

[Conab] Companhia Nacional de Abastecimento (2021a). Preço do alho. Conab. Available at: http://sisdep.conab.gov.br/precosiagroweb/. Accessed on: Aug. 15, 2021.

[Conab] Companhia Nacional de Abastecimento (2021b). Preços Agropecuários. Relatório de Insumos Agropecuários. Conab. Available in: https://www.conab.gov.br/info-agro/precos. Accessed on: Aug. 15, 2021.

[CQFS-RS/SC] Comissão de Química e Fertilidade do Solo (2004). Manual de adubação e de calagem para os Estados do Rio Grande do Sul e Santa Catarina. 10th ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo, Comissão de Química e Fertilidade do Solo.

[CQFS-RS/SC] Comissão de Química e Fertilidade do Solo (2016). Manual de calagem e adubação para os estados do Rio Grande do Sul e Santa Catarina. 11th ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo, Comissão de Química e Fertilidade do Solo.

Cunha, M. L. P., Aquino, L. A., Novais, R. F., Clemente, J. M., de Aquino, P. M. and Oliveira, T. F. (2016). Diagnosis of the nutritional status of garlic crops. Revista Brasileira de Ciência do Solo, 40, 1-14. https://doi.org/10.1590/18069657rbcs20140771

Diriba-Shiferaw, G., Nigussie-Dechassa, R., Kebede, W., Getachew, T. and Sharma, J. (2013). Growth and nutrients content and uptake of garlic (Allium sativum L.) as influenced by different types of fertilizers and soils. Science, Technology and Arts Research Journal, 2, 35-50. https://doi.org/10.4314/star.v2i3.98727

Donagema, G. K., Campos, D. V. B., Calderano, S. B., Teixeira, W. G. and Viana, J. H. M. (2011). Manual de métodos de análise de solos. 2nd ed. Rio de Janeiro: Embrapa Solos.

El-Metwally, I., Geries, L. and Saudy, H. (2022). Interactive effect of soil mulching and irrigation regime on yield, irrigation water use efficiency and weeds of trickle–irrigated onion. Archives Agronomy Soil of Science, 68, 1103-1116. https://doi.org/10.1080/03650340.2020.1869723

[Embrapa] Empresa Brasileira de Pesquisa Agropecuária (2009). Manual de análises químicas de solos, plantas e fertilizantes. 2nd ed. Brasília: Embrapa Informação Tecnológica.

Fan, Y., Ni, Z., Wang, S., Zhang, J. and Wu, S. (2021). Whole process phosphorus management strategy construction with phosphorus load characteristics, driver and efficiency from the materialflow perspective. Journal of Cleaner Production, 279, 122896. https://doi.org/10.1016/j.jclepro.2020.122896

[FAOSTAT] Food and Agriculture Organization of the United Nations. Statistics Division (2021). Value of agricultural production. FAOSTAT. Available at: https://www.fao.org/faostat/en/#data/QV. Accessed on: Aug. 10, 2021.

Fischer, P., Pöthig, R., Gücker, B. and Venohr, M. (2018). Phosphorus saturation and superficial fertilizer application as key parameters to assess the risk of diffuse phosphorus losses from agricultural soils in Brazil. Science of The Total Environment, 630, 1515-1527. https://doi.org/10.1016/j.scitotenv.2018.02.070

Fouda, K. F. (2020). Effect of phosphorus fertilization and Psb on garlic quality under organic farming system. Journal of Soil Sciences and Agricultural Engineering, 11, 661-666. https://doi.org/10.21608/jssae.2020.135757

Gelman, A. and Hill, J. (2007). Data analysis using regression and multilevel/hierarchical models. New York: Cambridge University Press.

Grando, D. L., Gatiboni, L. C., Mumbach, G. L., Dall'Orsoletta, D. J., Souza Junior, A. A. and Schmitt, D. E. (2021). Phosphorus in the runoff of soils with contrasting textures influenced by soil slope and pig slurry application. Agricutural Water Management, 258, 107178. https://doi.org/10.1016/j.agwat.2021.107178

Hahn, L., Parent, L. É., Paviani, A. C., Feltrim, A. L., Wamser, A. F., Rozane, D. E., Ender, M. M., Grando, D. L., Moura-Bueno, J. M. and Brunetto, G. (2022). Garlic (*Allium sativum*) feature-specific nutrient dosage based on using machine learning models. PLoS One, 17, e0268516. https://doi.org/10.1371/journal.pone.0268516

Hahn, L., Feltrim, A.L., Mattos M.E., Grando, D.L., Moura-Bueno, J. M., Stefanello, L.O., et al. (2024). Supplemental material. figshare. Figure. https://doi.org/10.6084/m9.figshare.26388250.v1

Hahn, L., Paviani, A. C., Feltrim, A. L., Wamser, A. F., Rozane D. E. and Reis, A. R. (2020). Nitrogen doses and nutritional diagnosis of virus-free garlic. Revista Brasileira de Ciência do Solo, 44, e0190067. https://doi.org/10.36783/18069657rbcs20190067

Hope, R. M. (2013). R Core Team. Rmisc: Ryan Miscellaneous.

[IBGE] Instituto Brasileiro de Geografia e Estatística (2020). PAM - Produção agrícola municipal. IBGE. Available at: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturastemporarias-e-permanentes.html?=&t=resultados. Accessed on: Oct. 10, 2021.

Joshi, R. U., Singh, A. K., Singh, V. P., Rai, R. and Joshi, P. (2023). A review on adaptation of banana (*Musa* spp.) to cold in subtropics. Plant Breeding, 142, 269-283. https://doi.org/10.1111/pbr.13088

Kulmann, M. S. de S., Sete, P. B., Paula, B. V. de, Stefanello, L. O., Schwalbert, R., Schwalbert, R. A., Arruda, W. S., Sans, G. A., Parcianello, C. F., Nicoloso, F. T., Melo, G. W. B. de, Santos, H. P. and Brunetto, G. (2020). Kinetic parameters govern of the uptake of nitrogen forms in 'Paulsen' and 'Magnolia' grapevine rootstocks. Science Horticultural, 264, 109174. https://doi.org/10.1016/j.scienta.2020.109174

Kyveryga, P., Caragea, P. C., Kaiser, M. S. and Blackmer, T. M. (2013). Predicting risk of reduced nitrogen fertilization using hierarchical models and on-farm data. Agronomy Journal, 105, 85-94. https://doi.org/10.2134/agronj2012.0218

Lambers, H., Martinoia, E. and Renton, M. (2015). Plant adaptations to severely phosphorus-impoverished soils. Current Opinion in Plant Biology, 25, 23-31. https://doi.org/10.1016/j.pbi.2015.04.002

Lawande, K. E., Khar, A., Mahajan, V., Srinivas, P. S., Sankar, V. and Singh, R. P. (2009). Onion and garlic research in India. Journal of Horticultural Sciences, 4, 91-119. https://doi.org/10.24154/jhs.v4i2.527

Li, X., Huang, L., Fang, H., Chen, M., Cui, Z., Sun, Z. and Reible, D. (2021). Phosphorus adsorption by sediment considering mineral composition and environmental factors. Environmental Science and Pollution Research, 28, 17495-17505. https://doi.org/10.1007/s11356-020-12206-9

Liang, Z., Liu, Y., Xu, Y. and Wagner, T. (2021). Bayesian change point quantile regression approach to enhance the understanding of shifting phytoplankton-dimethyl sulfide relationships in aquatic ecosystems. Water Research, 201, 117287. https://doi.org/10.1016/j.watres.2021.117287

Lima Neto, A. J. de, Neves, J. C. L., Martinez, H. E. P., Sousa, J. S. and Fernandes, L. V. (2020). Establishment of critical nutrient levels in soil and plant for eucalyptus. Revista Brasileira de Ciência do Solo, 44, e0190150. https://doi.org/10.36783/18069657RBCS20190150

Lucini, M. A. (2004). Manual prático de produção: Alho. 2nd ed. Bayer CropScience.

Luengo, R. F. A., Calbo, A. G., Lana, M. M., Moretti, C. L. and Henz, G. P. (1999). Classificação de hortaliças. Brasília: Embrapa Hortaliças.

Marodin, J. C., Resende, F. V., Gabriel, A., de Souza, R. J., de Resende, J. T. V., Camargo, C. K. and Zeist, A. R. (2019). Agronomic performance of both virus-infected and virus-free garlic with different seed bulbs and clove sizes. Pesquisa Agropecuária Brasileira, 54, 1-8. https://doi.org/10.1590/S1678-3921.PAB2019.V54.01448

Mendiburu, F. (2021). R Core Team. Agricolae: Statistical procedures for agricultural research.

Murphy, J. and Riley, J. P. (1962). A modified single solution methods for the determination of phosphate in natural waters. Analytica Chimica Acta, 27, 31-36. https://doi.org/10.1016/S0003-2670(00)88444-5

Nemadodzi, L., Araya, H., Nkomo, M., Ngezimana, W. and Mudau, N. F. (2017). Nitrogen, phosphorus and potassium effects on the physiology and response biomass yield of baby spinach (*Spinacia oleracea* L.). Journal of Plant Nutrition, 40, 2033-2044. https://doi.org/10.1080/01904167.2017.1346121

Noureldin, N. A., Saudy, H. S., Ashmawy, F. and Saed, H. M. (2013). Grain yield response index of bread wheat cultivars as influenced by nitrogen levels. Annals of Agricultural Sciences, 58, 147-152. https://doi.org/10.1016/j.aoas.2013.07.012

Oliveira, J. S., Inda, A. V., Barrón, V., Torrent, J., Tiecher, T. and Oliveira Camargo, F. A. (2020). Soil properties governing phosphorus adsorption in soils of Southern Brazil. Geoderma Regional, 22, e00318. https://doi.org/10.1016/j.geodrs.2020.e00318

Oliveira Neto, R. C., Justino Neto, J. F., Lana, R. M. Q., Santos, L. C. M., Pereira, A. I. de A. and Luz, J. M. Q. (2020). Soil organomineral fertilization in garlic crop. Comunicata Scientiae, 12, 1-5. Available in: https://www.comunicatascientiae.com.br/comunicata/article/view/3651

Penn, C. J. and Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture, 9, 120. https://doi.org/10.3390/agriculture9060120

Pinto, S. C. I., Furtini Neto, A. E., Moretti, B. S., Santos, C. F., Andrade, A. B. and Guelfi, D. (2021). Root morphology and joint uptake kinetics of phosphorus, potassium, calcium and magnesium in six eucalyptus clones. Communications in Soil Science and Plant Analysis, 52, 45-57. https://doi.org/10.1080/00103624.2020.1845358

Plummer, M. (2016). Rjags: Bayesian Graphical Models using MCMC. R package version.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna: R Core Team.

Rahman, M. K., Wang, X., Gao, D., Zhou, X. and Wu, F. (2021). Root exudates increase phosphorus availability in the tomato/potato onion intercropping system. Plant Soil, 464, 45-62. https://doi.org/10.1007/s11104-021-04935-8

Resende, J. T. V. de, Morales, R. G. F., Zanin, D. S., Resende, F. V., Paula, J. T. de, Dias, D. M. and Galvão, A. G. (2013). Caracterização morfológica, produtividade e rendimento comercial de cultivares de alho. Horticultura Brasileira, 31, 157-162. https://doi.org/10.1590/S0102-05362013000100025

Rodríguez, B. C., Durán Zuazo, V. H., Franco Tarifa, D., Cuadros Tavira, S., Sacristan, P. C. and García-Tejero, I. F. (2023). Irrigation Alternatives for Avocado (*Persea americana* Mill.) in the Mediterranean Subtropical Region in the Context of Climate Change: A Review. Agriculture, 13, 1049. https://doi.org/10.3390/agriculture13051049

Santos, L. P. D. dos, Cunha, M. L. P., Clemente, J. M., Oliveira, T. F., de Aquino, P. M., Assunção, N. S. and Aquino, L. A. (2017). Recovery efficiencies of nitrogen, phosphorus and potassium of the garlic crop. Journal of Plant Nutrition, 40, 624-631. https://doi.org/10.1080/01904167.2016.1240201

Saudy, H., Noureldin, N., Mubarak, M., Fares, W. and Elsayed, M. (2020). Cultivar selection as a tool for managing soil phosphorus and faba bean yield sustainability. Archives Agronomy Soil of Science, 66, 414-425. https://doi.org/10.1080/03650340.2019.1619078

Sebnie, W., Mengesha, M., Girmay, G. and Feyisa, T. (2018). Response of garlic (*Allium sativum* L.) to nitrogen and phosphorus under irrigation in Lasta district of Amhara Region, Ethiopia. Cogent Food & Agriculture, 4, 1532862. https://doi.org/10.1080/23311932.2018.1532862

Shaaban, A., El-Mageed, T. A. A., El-Momen, W. R. A., Saudy, H. S. and Al-Elwany, O. A. A. I. (2023). The integrated application of phosphorous and zinc affects the physiological status, yield and quality of canola grown in phosphorus-suffered deficiency saline soil. Gesunde Pflanz, 75, 1813-1821. https://doi.org/10.1007/s10343-023-00843-2

Shahin, M. G., Saudy, H. S., El-Bially, M. E., Abd El-Momen, W. R., El-Gabry, Y. A., Abd El-Samad, G. A. and Sayed, A. N. (2023). Physiological and agronomic responses and nutrient uptake of soybean genotypes cultivated under various sowing dates. Journal of Soil Science and Plant Nutrition, 23, 5145-5158. https://doi.org/10.1007/s42729-023-01389-y

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and Zhang, F. (2011). Phosphorus dynamics: From soil to plant. Plant Physiology, 156, 997-1005. https://doi.org/10.1104/pp.111.175232

Silva, F.C. (2009). Manual de análises químicas de solos, plantas e fertilizantes. 2. ed rev ampl. Brasília, DF: Embrapa Informação Tecnológica.

Sirisena, D. and Suriyagoda, L. D. B. (2018). Toward sustainable phosphorus management in Sri Lankan rice and vegetable-based cropping systems: A review. Agriculture Natural Resource, 52, 9-15. https://doi.org/10.1016/j.anres.2018.03.004

Soil Survey Staff (2014). Keys to soil taxonomy. Washington, D. C.: USDA-Natural Resources Conservation Service.

Stefanello, L., Schwalbert, R., Schwalbert, R., Tassinari, A., Garlet, L., De Conti, L., Ciotta, M., Ceretta, C., Ciampitti, I. and Brunetto, G. (2023). Phosphorus critical levels in soil and grapevine leaves for South Brazil vineyards: A Bayesian approach. European Journal of Agrononomy, 144, 126752. https://doi.org/10.1016/j.eja.2023.126752

Sucunza, F. A., Gutierrez Boem, F. H., Garcia, F. O., Boxler, M. and Rubio, G. (2018). Long-term phosphorus fertilization of wheat, soybean and maize on Mollisols: Soil test trends, critical levels and balances. European Journal of Agronomy, 96, 87-95. https://doi.org/10.1016/j.eja.2018.03.004

Sun, B., Gao, Y., Wu, X., Ma, H., Zheng, C., Wang, X., Zhang, H., Li, Z. and Yang, H. (2020). The relative contributions of pH, organic anions, and phosphatase to rhizosphere soil phosphorus mobilization and crop phosphorus uptake in maize/alfalfa polyculture. Plant Soil, 447, 117-133. https://doi.org/10.1007/s11104-019-04110-0

Tedesco, M. J., Gianello, C., Bissani, C. A., Bohnen, H. and Volkweiss, S. J. (1995). Analysis of soils, plants and other materials. 2nd ed. Porto Alegre: UFRGS.

Triharyanto, E., Putri, G. F. A., Putri, S. and Muliawati, E. S. (2021). The yield potency of various types of garlic planting materials. IOP Conference Series: Earth Environmental Science, 824, 012062. https://doi.org/10.1088/1755-1315/824/1/012062

Tyler, K. B., May, D. M., Guerard, J. P., Ririe, D. and Hatakeda, J. J. (1988). Diagnosing nutrient needs of garlic. California Agriculture, 28-29.

Vaccari, D. A., Powers, S. M. and Liu, X. (2019). Demand-driven model for global phosphate rock suggests paths for phosphorus sustainability. Environmental Science and Technology, 53, 10417-10425. https://doi.org/10.1021/acs.est.9b02464

Vives-Peris, V., de Ollas, C., Gómez-Cadenas, A. and Pérez-Clemente, R. M. (2020). Root exudates: from plant to rhizosphere and beyond. Plant Cell Reports, 39, 3-17. https://doi.org/10.1007/s00299-019-02447-5

Walkley, A. and Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37, 29-38. https://doi.org/10.1097/00010694-193401000-00003

Wang, J., Chen, Y., Wang, P., Li, Y. S., Wang, G., Liu, P. and Khan, A. (2018). Leaf gas exchange, phosphorus uptake, growth and yield responses of cotton cultivars to different phosphorus rates. Photosynthetica, 56, 1414-1421. https://doi.org/10.1007/s11099-018-0845-1

Wang, K., Hu, Q., Wei, Y., Yin, H., Sun, C. and Liu, G. (2021). Uptake kinetics of NH^{+4}, NO^{-3} and H_2PO_4- by Typha orientalis, Acorus calamus L., Lythrum salicaria L., Sagittaria trifolia L. and Alisma plantago-aquatica Linn. Sustainability, 13, 434. https://doi.org/10.3390/su13010434

Wang, M., Ye, Y., Chu, X., Zhao, Y., Zhang, S., Chen, H., Qin, W. and Wang, Y. (2022). Responses of garlic quality and yields to various types and rates of potassium fertilizer applications. Hort Science, 57, 72-80. https://doi.org/10.21273/HORTSCI15984-21

Wickham, H., Winston Chang, W., Henry, L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D. and Brand, T. (2021). ggplot2: Create elegant data visualisations using the grammar of graphics. R package version.

Wu, C., Wang, M., Cheng, Z. and Meng, H. (2016). Response of garlic (*Allium sativum* L.) bolting and bulbing to temperature and photoperiod treatments. Biology Open, 5, 507-518. https://doi.org/10.1242/bio.016444

Yu, K. and Moyeed, R. A. (2001). Bayesian quantile regression. Statistics & Probability Letters, 54, 437-447. https://doi.org/10.1016/S0167-7152(01)00124-9