



Photosynthetic, Nutritional Efficiency, and Productivity of Fig Trees Under Pruning Management and Fertilization with Potassium Silicate in the Semi-Arid Region

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Abstract

Purpose The fig tree (*Ficus carica* L.) is a remarkable species, demonstrating its adaptability to environments with consistently high temperatures, such as semi-arid regions. This adaptability underscores the importance of selecting the correct management for its cultivation, as it directly influences the plant's physiology and development, and consequently, its productivity. Our study aimed to evaluate the effects of potassium silicate application and pruning management in fig trees to optimize photosynthetic efficiency, biomass accumulation, and productivity under a semi-arid climate.

Methods The experimental design employed was a randomized block design in a 5 × 3 factorial scheme, with five blocks and one plant per plot. The treatments consisted of five potassium silicate doses (0.0%, 0.5%, 1.0%, 1.5%, and 2.0%) applied foliarly, along with three numbers of productive branches (3, 6, and 9).

Results Applying potassium silicate at doses (0.5%, 1.5%, and 2.0%) associated with six and nine productive branches increased the photosynthesis of fig trees. The 0.5% dose produced subtle changes in the photosynthetic processes of fig trees, primarily reflected in productivity, resulting in increases of 59.91% in productivity and 49.08% in dry matter accumulation in the aerial parts of the plants.

Conclusions The application of potassium silicate, combined with pruning management, optimized the phytotechnical variables of the 'Roxo de Valinhos' fig tree under semi-arid conditions. Fig trees with six productive branches subjected to applications of 0.5% potassium silicate showed significant improvements in leaf gas exchange, increased net photosynthesis, and a considerable increase in biomass accumulation and plant productivity.

Highlights

- Potassium silicate is an appropriate way to apply Si to the fig tree "Roxo de Valinhos."
- Potassium silicate, when used in pruning management, optimized the phytotechniques characteristics of the fig tree "Roxo de Valinhos."
- Applying potassium silicate increased net photosynthesis, biomass accumulation, and productivity.

Keywords *Ficus carica* L. · K₂SiO₃ · Roxo de Valinhos · Leaf gas exchange · Number of productive branches

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1 Introduction

The fig tree (*Ficus carica* L.) stands out as one of the oldest cultivated species (medicinal and edible) due to its adaptation to humid subtropical and temperate climates. It is grown in several regions of the world [1, 2]. Pruning emerges as a crucial technique to ensure adequate fig production. Without this management, the plants exhibit disordered growth, self-shading, and reduced fruit production [3–5]. Pruning not only organizes the plant canopy but also optimizes light distribution within it. It maximizes solar interception and, consequently, photosynthetic efficiency, resulting in increased dry matter production, higher fruit yield, and improved fruit quality [1]. Previous research highlights the effectiveness of pruning in several plants, such as fig [3–8], peach [9], sweet cherries [10], and lemon [11], among others, evidencing its positive impact on fruit yield and quality.

The fig tree has production potential in the semi-arid regions of Northeast Brazil due to its adaptability to constant high temperatures. This allows for an earlier cycle compared to other producing areas in the country (South and Southeast), in addition to low relative humidity, which may lead to a lower incidence of rust caused by *Cerotelium fici*, the primary pathogen of the crop [12]. However, production under high temperatures and high radiation is deleterious to plant growth and biomass, as it interferes with protein metabolism, enzymatic processes, pigment synthesis, photosynthetic efficiency, and transpiration rate. In extreme conditions, it can cause wilting and sunburn [13].

Applying silicon (Si) is an effective strategy to mitigate heat stress, as it acts on stomatal regulation and maintains water balance [14, 15]. Si deposits within the cell wall compartments of the xylem and other vascular tissues prevent cell compression during excessive transpiration [16, 17]. In this context, studies have confirmed the potential of Si to mitigate heat stress within cells by reducing oxidative damage, thereby improving plant tolerance to high temperatures in several species [14–20].

In addition to its benefits in controlling heat stress, Si supplementation maintains ionic homeostasis, increases photosynthesis and stomatal conductance, reduces transpiration and ionic toxicity, and regulates the biosynthesis of solutes and plant hormones [15]. Furthermore, it enhances growth and biomass, manages essential nutrients, maintains structural rigidity, elicits secondary metabolites related to stress resistance, and regulates genes involved in various physiological processes [14, 15, 21, 22].

However, understanding physiological limitations and analyzing responses to environmental conditions are fundamental, highlighting the importance of ecophysiological

studies. Plant ecophysiology provides information on the response thresholds to specific ecological conditions for each species or variety studied [23]. Although studies on the management and adaptation of new species, such as fig, generally focus on aspects of fruit production and quality, it is crucial to explore the ecophysiological conditions under which these plants develop [24]. However, studies in this context are scarce in the literature.

Ecophysiological research involves analyzing several parameters, including stomatal conductance (g_s), transpiration rate (E), intrinsic water use efficiency (WUE_i), net photosynthetic rate (A_N), internal CO_2 concentration (C_i), leaf temperature (LT), and instantaneous carboxylation efficiency ($A_N C_i$). These parameters, which are essential for evaluating photosynthetic pigment levels and the maximum photochemical efficiency of PSII (F_v/F_m), are crucial for understanding the state of adaptation, growth, and development of plants in their environment [23].

Photosynthesis is considered the basis for plant growth and yield, and management practices, including the application of specific technologies, influence it. Therefore, it is necessary to develop studies aimed at manipulating photosynthetic performance to enhance plant photosynthetic capacity, thereby increasing production and biomass yield [25]. Thus, we hypothesize that specific management practices, such as pruning, combined with the strategic application of potassium silicate, can optimize not only fruit yield but also improve their nutritional quality and resistance to adverse conditions, especially in semi-arid climates. Therefore, it is assumed that these management techniques can maximize photosynthetic efficiency, reduce the effects of heat stress, and promote beneficial ecophysiological adaptations, thereby increasing fig biomass and productivity. Given this assumption, the objective was to investigate the impact of potassium silicate application and pruning management on optimizing photosynthetic efficiency, biomass accumulation, and productivity of the fig tree under a semi-arid climate.

2 Materials and Methods

2.1 Characterization of the Experimental Area

The study was carried out in the educational orchard of the Federal Rural University of Semi-Arid Region (UFERSA), in the municipality of Mossoró, the western region of the state of Rio Grande do Norte, whose geographic coordinates are $5^{\circ} 11' 15''$ S latitude and $37^{\circ} 20' 39''$ W longitude, with an altitude of 18 m and flat relief. The region's climate, according to the Köppen climate classification, is BSh, hot tropical semi-arid, with an average annual rainfall of 673.9 mm, an average temperature of $27.4^{\circ}C$, and two

well-defined periods: a dry (prolonged) and a wet (short and irregular) [26].

During the experimental period, which ran from September 2021 to May 2022, the following meteorological data were collected from UFERSA's Automatic Meteorological Station (EMA): maximum, average, and minimum temperature, maximum and minimum relative air humidity, and rainfall (Fig. 1).

Before the experiment was implemented, soil samples were collected from the experimental area at a depth of 0–20 cm, dried, crushed, and sieved through a 2 mm mesh

(air-dried fine soil—TFSA) for chemical analysis. The same procedure was carried out at the end of the experiment [27] (Table 1).

2.2 Materials and Cultivation Management

The plants used in this study are *Ficus carica* L., specifically the "Roxo de Valinhos" cultivar. They are eight years old and spaced 2 m × 1.5 m apart. The experimental period spanned September 2021 to May 2022, totaling eight months.

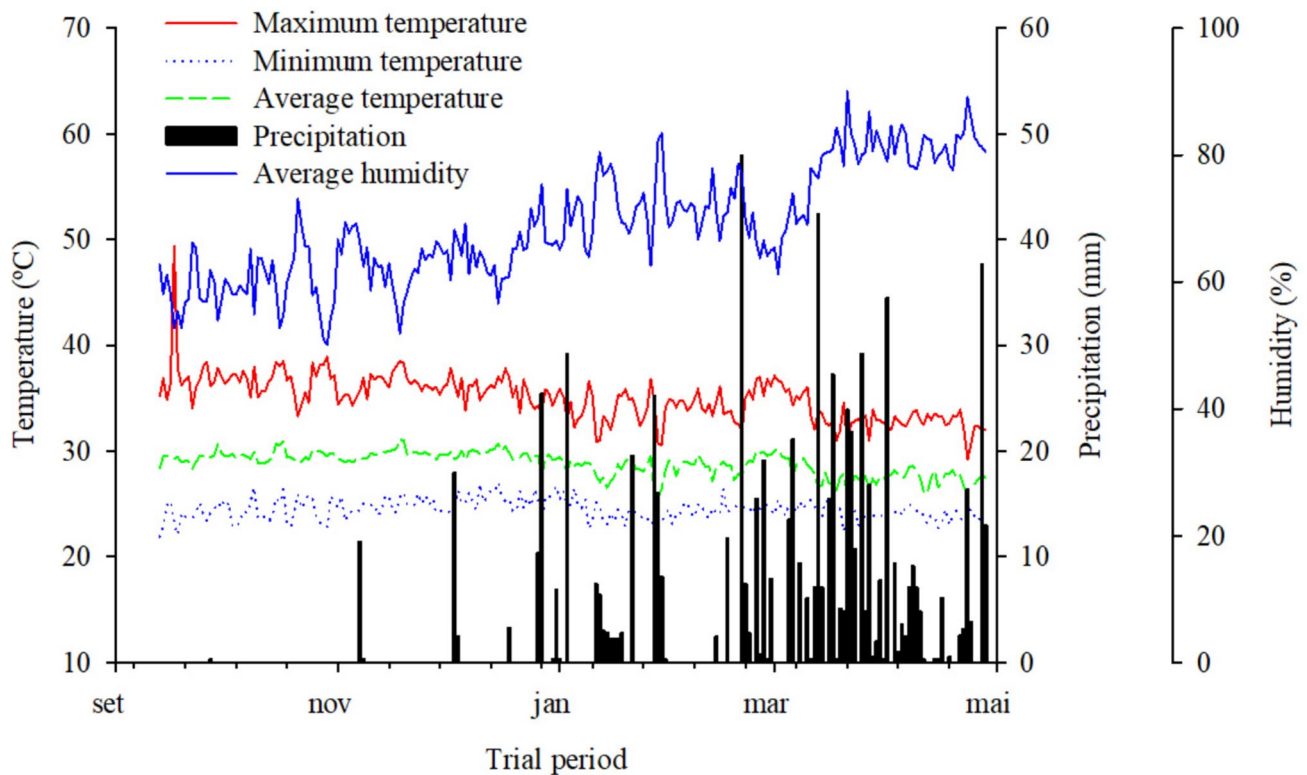


Fig. 1 Air temperature (°C), relative humidity (%), and precipitation (mm) during the experiment in Mossoró, Rio Grande do Norte, Brazil

Table 1 Chemical characteristics of the soil in the experimental area at the beginning and end of the experiment. Mossoró, RN – Brazil

Samples	pH	CE	Mat. Org		P	K ⁺	Na ⁺	
	H ₂ O	dS m ¹	g kg ¹		mg dm ³			
Start	7.47	0.11	6.66		60.75	272.10	74.30	
End	7.52	0.18	7.78		53.70	284.30	124.60	
OC	7.30	5.43			274.78	5213.50	683.30	
Samples	Ca ²⁺	Mg ²⁺	Al ³⁺	(H + Al)	SB	CTC	V	PST
	cmolc dm ³				%			
Start	6.01	3.31	0	0	10.73	10.73	100	5.00
End	4.74	1.34	0	0	7.08	7.08	100	6.21
OC	15.60	6.21	0	0	39.06	39.06	100	10.14

P, K⁺, Na⁺: Mehlich extractant 1; Al³⁺; (H + Al)=0; Ca²⁺, Mg²⁺: KCl extractant 1.0 mol L⁻¹; OC Organic compound, pH Hydrogen potential, CE Electrical conductivity, SB Sum of base, CTC Cation exchange capacity, Org. Mat. Walkley–Black Wet Digestion, PST Percentage of exchangeable sodium

The potassium silicate was obtained commercially (Pro-Silicon, Rigrantec, Brazil). The product's composition corresponded to K_2O (10%) and SiO_2 (10%). Potassium silicate was applied foliarly using a pre-compression sprayer with a capacity of 2.0 L (Generic, Pul 04). Applying approximately 150 mL per plant to the drop point, the dilution was performed with distilled water, with the respective mL being measured for each concentration used, in the proportion of 1:1. The applications were performed 45 days after production pruning, with intervals of 15 days, in the late afternoon, approximately 5:00 p.m., totaling five applications until the end of the cycle.

The irrigation system was a micro-sprinkler system, featuring a 75 L h^{-1} Rondo Rivulis micro-sprinkler on a 60 cm stake. It operated for one hour daily, with one sprinkler per plant, and a break was taken on rainy days.

Regular cleaning between the rows was carried out using a brush cutter, and manual weeding was used to control weeds. Stealing branches and new shoots were removed with pruning shears whenever necessary.

After production pruning, approximately two weeks later, the plants received a single application of 45 g of phosphorus, 63 g of nitrogen, and 45 g of potassium per plant, divided into three separate applications. MAP (10% N, 46% P_2O_5) was used as a phosphorus source. As a source of N, ammonium sulfate (22% N) was used, and as a source of K, potassium chloride (60% K) was used, based on the results of the soil analysis and the recommendations for essential fertilization of the crop [28]. 10 kg of organic compost was also applied, as recommended by [12].

2.3 Experimental Design

The experimental design employed was a randomized block design in a 5×3 factorial scheme, with five blocks and one plant per plot. The first factor consisted of five doses of potassium silicate (0.0%, 0.5%, 1.0%, 1.5%, and 2.0%), and the second factor consisted of three production prunings (three, six, and nine productive branches).

Cleaning and pruning remove all vegetative branches from the plant, leaving only the primary branches (legs). Cleaning and pruning were performed on August 26, 2021, marking the beginning of the cycle. After the plants' vegetative development, approximately 45 days after cleaning and pruning, production pruning was performed, selecting well-developed, well-distributed branches and discarding those with growth directed towards the canopy's interior or downwards (Fig. 2).

2.4 Variables Analyzed

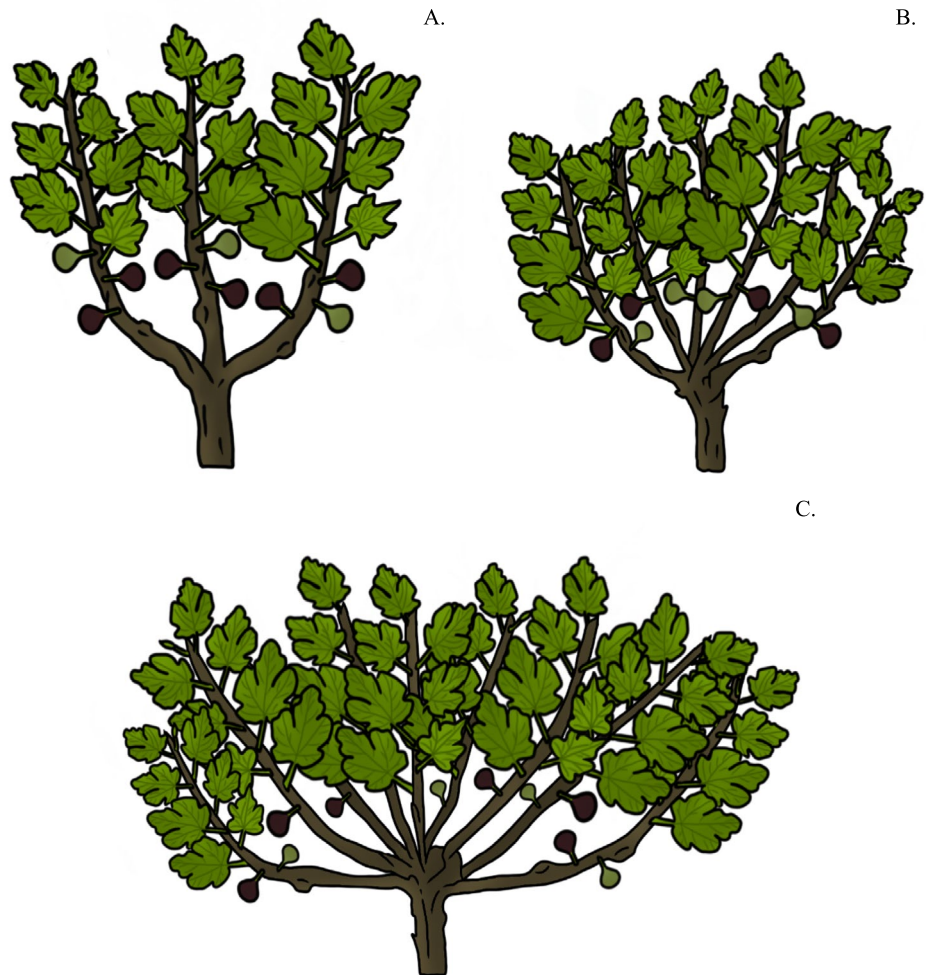
The following variables were analyzed:

Gas Exchange The plants were evaluated only once, at the beginning of the production period (150 days after pruning), between 7:00 and 9:00 a.m. The evaluations were performed on fully expanded leaves located in the upper third of each plant, with a portable infrared carbon dioxide analyzer (IRGA), model LCPro + Portable Photosynthesis System® (ADC Bio Scientific Limited, UK), LCPro + with temperature control at $25\text{ }^{\circ}\text{C}$, irradiation of $1200\text{ }\mu\text{mol photons m}^{-2}\text{ s}^{-1}$, and airflow of 200 mL min^{-1} . Obtain net photosynthesis (A_N) in $\mu\text{mol (CO}_2\text{) m}^{-2}\text{ s}^{-1}$, transpiration (E) in $\text{mmol (H}_2\text{O) m}^{-2}\text{ s}^{-1}$, stomatal conductance (g_s) in $\text{mol (H}_2\text{O) m}^{-2}\text{ s}^{-1}$, internal CO_2 concentration (C_i) in $\text{mol (CO}_2\text{) m}^{-2}\text{ s}^{-1}$, and leaf temperature (Lt) in $^{\circ}\text{C}$. Using this data, the instantaneous water use efficiency (WUE_i) in $\mu\text{mol m}^{-2}\text{ s}^{-1}/\text{mmol (H}_2\text{O) m}^{-2}\text{ s}^{-1}$ and the instantaneous carboxylation efficiency (A_N/C_i) were quantified [29]. Chlorophyll fluorescence was measured using a pulse-modulated fluorometer (model OS5p) from Opti Science. This protocol used an actinic illumination source with a saturating multi-flash pulse, coupled to a photosynthetically active radiation (PAR) determination clip, after the leaves had been adapted to darkness for 30 min. Under these conditions, the maximum quantum efficiency of PSII (F_v/F_m) was estimated [29]. The chlorophyll content index was determined using an electronic chlorophyll content meter (ClorofiLOG®, CFL 1030) (Falker, Porto Alegre, Brazil) only once at the beginning of the production period (150 days after pruning) in all plants that make up the experimental unit. In each plant, young and fully expanded leaves were selected from the upper middle third, free of pest or disease damage, and measured at three equidistant points on the adaxial surface of each leaf. The values of chlorophyll *a*, chlorophyll *b*, and total were obtained.

Nutritional Status The nutritional content of the leaves was determined by selecting young, fully expanded leaves exposed to sunlight from the upper-middle third of each plant in the experimental unit, without any signs of pest or disease attack [30]. Then, the contents of silicon (Si), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were determined after sulfuric digestion, and iron (Fe), zinc (Zn), and manganese (Mn) after dry digestion [27].

Biomass Accumulation and Productivity To assess biomass after harvest (May 2023), all branches were cut to determine dry matter. The plant raw material was dried in a forced circulation oven at $65\text{ }^{\circ}\text{C}$ (NE, 400D) until a constant mass was obtained, which was then measured on a semi-analytical balance (PRLabor, Ux4200h-Shimadzu). To determine productivity, the ratio of commercial production to area was calculated from the number of plants, and the results were expressed as tons per hectare (t ha^{-1}).

Fig. 2 Types of production pruning performed: **A.** three branches, **B.** six branches, and **C.** nine productive branches (C.) in semi-arid conditions. Mossoró, Rio Grande do Norte, Brazil



2.5 Statistical Analysis

The results were subjected to the Shapiro–Wilk normality test and the Bartlett's test of homogeneity. Subsequently, they were subjected to an analysis of variance using the F-test at a 5% significance level. In the case of significance, the treatments were subjected to a mean *t*-test (LSD) using the statistical program System for Analysis of Variance – SISVAR v. 5.6 [31].

3 Results

3.1 Gas Exchanges

The gas exchanges of fig trees were significantly influenced by the two factors studied: potassium silicate doses and different numbers of productive branches. There was a significant interaction for internal CO₂ concentration (*C_i*), stomatal conductance (*g_s*), instantaneous carboxylation efficiency (*A_N/C_i*), net photosynthesis (*A_N*), the maximum quantum

efficiency of PSII (*F_v/F_m*) (*p* < 0.01), transpiration (*E*) and leaf temperature (*LT*) (°C) (*p* < 0.05). Water use efficiency (*WUE_i*) was significantly influenced only by potassium silicate doses applied at the level of (*p* < 0.01). Only chlorophyll *a*, *b*, and total contents were not significantly influenced by the treatments studied.

The lowest stomatal conductance (*g_s*) was obtained in plants that received 1.0% potassium silicate, regardless of the number of productive branches evaluated, obtaining values of 0.416, 0.416, and 0.434 mol (H₂O) m⁻² s⁻¹ for branches three, six, and nine, respectively (Fig. 3A). In plants with three productive branches, the highest stomatal conductances were obtained with 2.0% potassium silicate 0.522 mol (H₂O) m⁻² s⁻¹, followed by 0.5% with 0.506 mol (H₂O) m⁻² s⁻¹, statistically equal (Fig. 3A), representing a difference of approximately 20.30% in the stomatal opening of fig trees, comparing the highest value (0.522) and the lowest value (0.416).

With six productive branches, the highest *g_s* were obtained in plants that received the 0.5% dose, registering an increase of 19.69% compared to the lowest value.

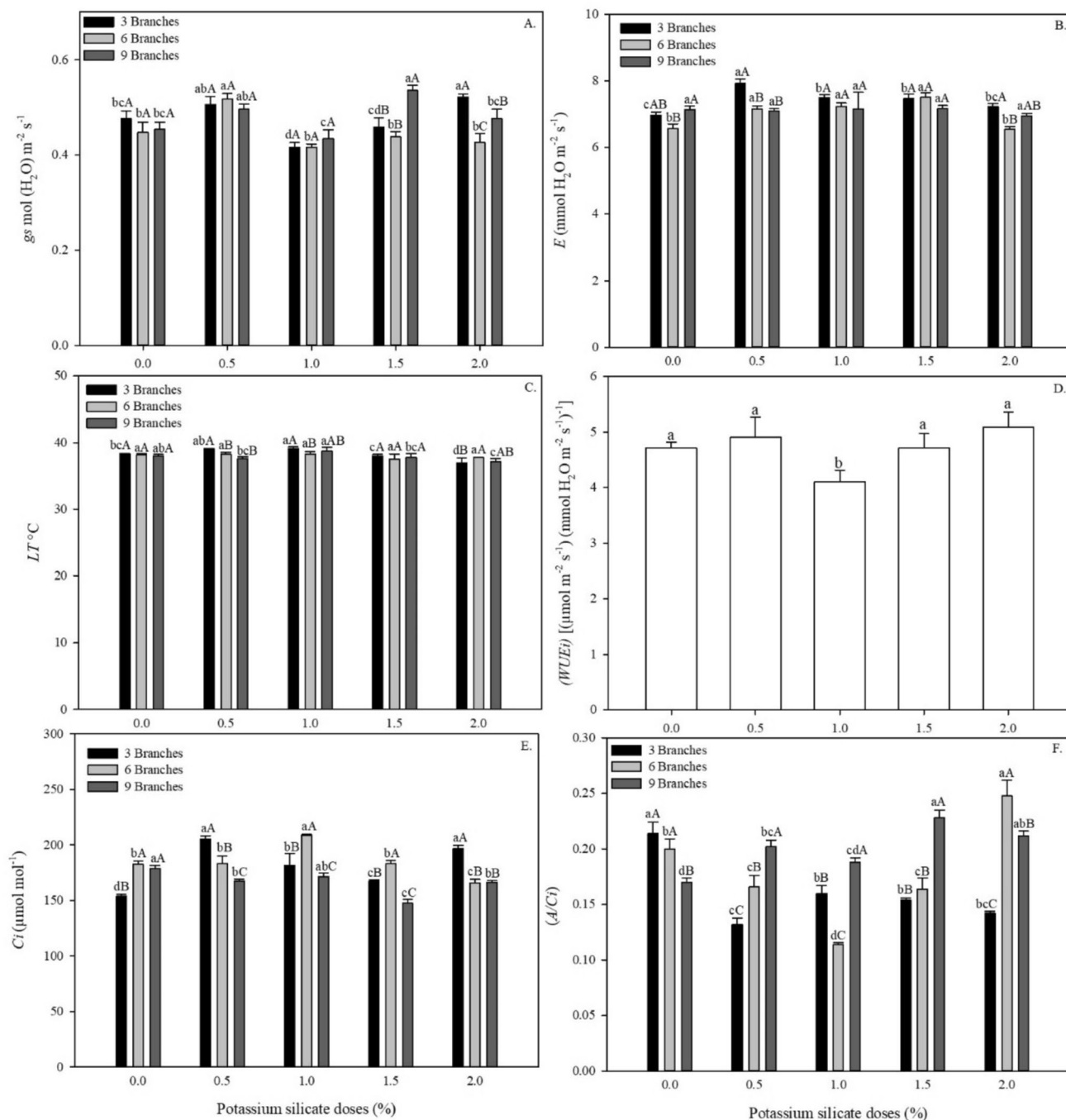


Fig. 3 Stomatal conductance (g_s) ($\text{mol de H}_2\text{O m}^{-2} \text{s}^{-1}$) (A), transpiration (E) ($\text{mmol (H}_2\text{O) m}^{-2} \text{s}^{-1}$) (B), leaf temperature (LT , $^{\circ}\text{C}$) (C), instantaneous water use efficiency (WUE_i) ($\mu\text{mol (CO}_2\text{) m}^{-2} \text{s}^{-1} / \text{mmol (H}_2\text{O) m}^{-2} \text{s}^{-1}$) (D)***, internal CO_2 concentration (C_i) ($\mu\text{mol mol (CO}_2\text{) m}^{-2} \text{s}^{-1}$) (E), instantaneous carboxylation efficiency (A_N/C_i) (F) in fig trees subjected to different doses of potassium

silicate and numbers of productive branches. Mossoró-RN. *Means followed by the same lowercase letter between branches and uppercase letter within dose do not differ from each other by the LSD test ($p > 0.05$). ** Means followed by the same lowercase letter do not differ from each other by the LSD test ($p > 0.05$)

The other doses did not differ statistically from each other. Plants with nine productive branches had higher g_s with the application of 1.5% and 0.5% 0.536 and 0.496 mol

($\text{H}_2\text{O) m}^{-2} \text{s}^{-1}$, equivalent to an increase of 19.03% compared to the lowest g_s obtained (0.434) (Fig. 3A).

The control plants (0.0%) subjected to three productive branches showed the lowest transpiration (E) of $6.97 \text{ mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1}$. The highest transpiration rate was observed with the application of 0.5% potassium silicate, at $7.92 \text{ mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1}$. The 1.0% and 1.5% doses had transpiration rates that were statistically equal and lower than that of the 0.5% dose (Fig. 3B). In the plants with six productive branches, the lowest E was obtained at a potassium silicate dose of 2.0%, corresponding to $6.55 \text{ mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1}$, followed by the control plants at $6.57 \text{ mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1}$, which were statistically equal. The other doses of potassium silicate applied did not differ statistically and showed higher values (Fig. 3B). The plants with nine productive branches had no statistical difference between the treatments studied. Plants with three productive branches and application of 0.5% and 1.0% potassium silicate had the highest leaf temperatures (LT) of 39.04 and 39.12°C , respectively. However, when the potassium silicate doses were increased to 1.5% and 2.0%, LT was reduced to 37.98°C and 36.94°C , respectively (Fig. 3C). Plants with nine branches, associated with the 1.0% dose, provided the highest LT of 38.70°C , followed by the control plants at 38°C , which were statistically equivalent. Plants with nine branches associated with 2.0% resulted in the lowest LT of 37.16°C . Plants with six productive branches did not show significant differences among treatments (Fig. 3C).

The application of 1.0% potassium silicate resulted in a lower instantaneous water use efficiency (WUE_i) of $4.11 (\mu\text{mol m}^{-2} \text{ s}^{-1}/\text{mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1})^{-1}$. Although the other dosages did not differ statistically, the doses of 0.5% and 2.0% potassium silicate promoted higher WUE_i values of 4.90 and $5.09 (\mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}/\text{mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1})^{-1}$, respectively, representing an increase in instantaneous water use efficiency of 19.25% about the dose of 1.0% (Fig. 3D).

Plants with three productive branches, treated with 0.5% and 2.0% potassium silicate, had the highest C_i values, corresponding to 205.25 and $197 \mu\text{mol mol}^{-1}$, respectively. The lowest C_i was observed in the control plants at $153.60 \mu\text{mol mol}^{-1}$ (Fig. 3E). Plants with six productive branches had the highest C_i at a 1.0% potassium silicate concentration, $208.45 \mu\text{mol mol}^{-1}$. Plants with six branches, treated with 2.0% potassium silicate, exhibited the lowest C_i of $165.80 \mu\text{mol mol}^{-1}$ (Fig. 3E). In the control treatment, plants with nine branches had the highest CO_2 concentration, $179.00 \mu\text{mol mol}^{-1}$, which did not differ statistically from the 1.0% dose ($171.40 \mu\text{mol mol}^{-1}$; Fig. 3E). The other potassium silicate doses used resulted in reduced internal CO_2 concentrations, with the 1.5% dose yielding the most notable effect, as indicated by a lower C_i of $147.40 \mu\text{mol mol}^{-1}$ (Fig. 3E).

The instantaneous carboxylation efficiency (A_N/C_i) behaved similarly to C_i for the different numbers of productive branches studied. Plants with three productive

branches showed higher efficiency in the control plants (0.214). Due to the accumulation of C_i , plants subjected to 0.5% and 2.0% doses had lower efficiencies of 0.132 and 0.142, respectively (Fig. 3F).

Plants with six productive branches, treated with 2.0% potassium silicate, showed a higher efficiency of 0.248. However, the 1.0% dose resulted in a lower A_N/C_i of 0.114. Plants with nine productive branches and the application of 1.5% and 2.0% potassium silicate obtained the highest A_N/C_i values, 0.228 and 0.212, respectively, which were statistically equal. Control plants with nine productive branches had an A_N/C_i of 0.170, a 25.44% reduction compared to the 1.5% dose, which provided the best efficiency (Fig. 3F).

Fig trees with three productive branches that received potassium silicate applications produced less net photosynthesis (A_N). The lowest values were recorded at doses of 0.5%, 2.0%, 1.5%, 29.94 , 28.14 , and $27.81 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$, respectively, except for the dose of 1.0%, which provided more excellent production of A_N $35.24 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$, not differing statistically from the control plants, with $33.65 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$ (Fig. 4A).

Fig trees with six productive branches, associated with 2.0% potassium silicate, yielded higher A_N values of $36.77 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$. The 1.0% dose resulted in lower A_N production with $23.76 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$. Fig trees with nine productive branches associated with the 0.5%, 1.5%, and 2.0% doses provided higher A_N 33.53 , 34.45 , and $34.22 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$, respectively. The lowest A_N was observed with 1.0% potassium silicate at $31.21 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$, followed by the control plants at $29.74 \mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$, which was statistically equal. The applications of potassium silicate doses (0.5%, 1.5%, and 2.0%), except for 1.0%, caused an increase in the photosynthesis production of fig trees of approximately 11.30, 13.67, and 13.09%, respectively, compared to the control plants (Fig. 4A).

Fig trees with three productive branches had higher F_v/F_m values at a 1.5% dose (0.79), followed by the control plants (0.78), which were statistically equal. The highest potassium silicate dose applied reduced F_v/F_m to 0.76. In plants with six productive branches, the highest values were obtained with 1.0% (0.79), and in the control plants (0.79), which did not differ. Increasing the doses to 1.5% and 2.0% resulted in a reduction in the F_v/F_m values to 0.76, which did not differ statistically. Fig trees with nine productive branches showed the highest F_v/F_m values in the control plants (0.5%, 0.78), and the lowest value was obtained with 1.5% (0.76; Fig. 4B).

3.2 Biomass Accumulation and Productivity

The dry mass of the aerial part of the fig trees was significantly influenced by potassium silicate doses and by the

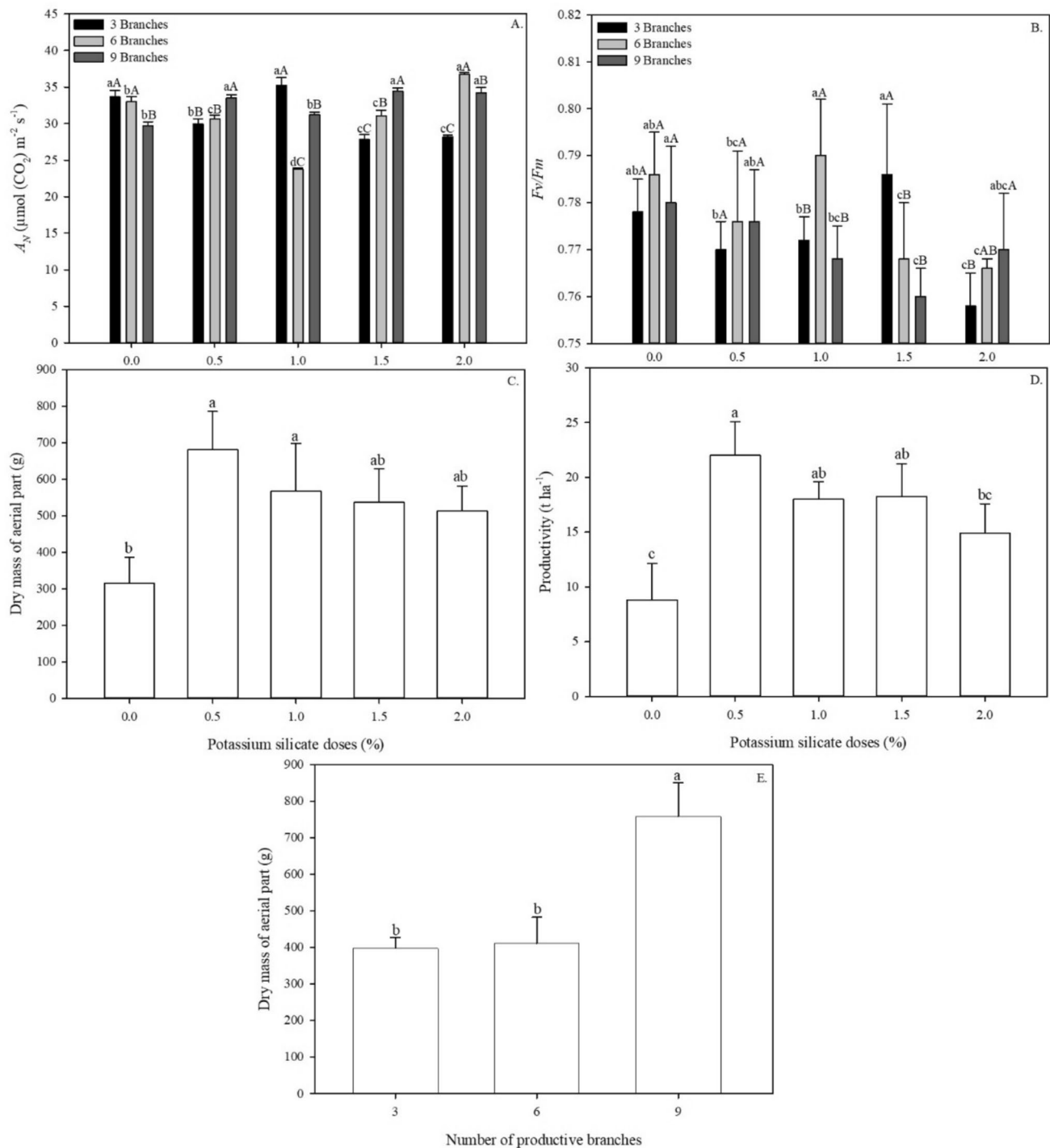


Fig. 4 Net photosynthesis (A_N) ($\mu\text{mol}(\text{CO}_2) \text{m}^{-2} \text{s}^{-1}$) (A), maximum quantum efficiency of PSII (F_v/F_m) (B), dry mass of aerial part (g) (C e E) e Productivity (t ha^{-1}) (D) in fig trees subjected to different doses of potassium silicate and numbers of productive branches.

*Means followed by the same lowercase letter for the branches and uppercase within the dose do not differ from each other by the LSD test ($p > 0.05$)

different numbers of productive branches, separately at the level of ($p < 0.01$) and ($p < 0.05$), respectively. Productivity was significantly influenced only by potassium silicate doses applied at the level ($p < 0.01$). The potassium silicate doses

used had a positive effect on the dry mass of the fig trees' aerial parts, and all doses increased biomass compared to the control plants. The highest value of the dry mass of the aerial part was obtained with a dose of 0.5% (681 g); however,

with doses above 0.5% potassium silicate, there were significant reductions in the dry mass of the aerial part, although they were consistently higher than the control (0.0%). The application of potassium silicate increased by 49.08% at 0.5%, 44.50% at 1.0%, 41.38% at 1.5%, and 38.70% at 2.0% compared with the control plants (Fig. 4C). Fig trees with nine productive branches produced more biomass (758.72 g) than those with six or three branches (411.20 and 397.80 g, respectively), which did not differ statistically from each other. The use of nine productive branches promoted an increase of 47.57% in the biomass of fig trees compared to plants with three productive branches (Fig. 4E).

Fig trees exhibited higher productivity with the 0.5% potassium silicate dose (22.00 t ha⁻¹), representing a 59.91% increase compared to the control plants, which had the lowest productivity (8.82 t ha⁻¹). The other potassium silicate doses (1.5%, 1.0%, and 2.0%) also promoted a considerable increase in fig tree productivity, with gains of 51.67%, 51%, and 40.76%, respectively, compared to the control plants (Fig. 4D).

3.3 Nutritional Status

The two factors studied also affected the leaves' nutritional composition. There was a significant interaction between potassium silicate doses and the number of productive branches for the contents of Si, N, P, K, Ca, and Fe ($p < 0.01$) and Mg, Mn, and Zn ($p < 0.05$). Fig trees with three productive branches showed the highest silicon content at the 1.5% dose of 10.50 g kg⁻¹, and the lowest content was found in the control plants at 8.42 g kg⁻¹, equivalent to a 20% increase in the silicon content of fig trees with three branches. Plants with six branches also showed higher silicon content at the 1.5% dose of 11.28 g kg⁻¹; however, in fig trees with nine productive branches, the highest silicon content was found at the 0.5% dose with 12.04 g kg⁻¹, representing an increase of 24.58% to the control plants. Additionally, it is noteworthy that the 1.5% and 0.5% doses resulted in the most significant silicon accumulation in the plants, regardless of the number of branches studied (Fig. 5A).

The highest nitrogen content in fig trees with three productive branches was 2.0% (36.79 g kg⁻¹), which did not differ statistically from 0.5% (35.78 g kg⁻¹). The lowest value was obtained in the control plants at 33.65 g kg⁻¹. Plants with six productive branches had the highest nitrogen content, with 0.5% potassium silicate at 37.36 g kg⁻¹, and the lowest value was obtained in control plants at 31.93 g kg⁻¹. Fig trees with nine productive branches had the highest nitrogen content at the 1.5% dose of 36.29 g kg⁻¹. However, the lowest value was observed in plants treated with 2.0% potassium silicate (Fig. 5B).

The phosphorus content varied with both the potassium silicate dose and the number of productive branches studied.

In plants with three branches, the highest content was found with 1.0% potassium silicate (0.59 g kg⁻¹), and the lowest contents were seen with doses of 0.0%, 1.5%, and 2.0%, which were statistically equal. Fig trees with six productive branches had the highest phosphorus content, at 0.5% (0.74 g kg⁻¹), and the other doses did not differ significantly from this value. However, with nine productive branches, the highest phosphorus content was obtained in the control plants (0.53 g kg⁻¹), and the dose of 0.5% resulted in the lowest value (0.41 g kg⁻¹) (Fig. 5C).

Plants with three productive branches had the highest potassium content with the application of 2.0% potassium silicate (20.23 g kg⁻¹), and the lowest content was found in plants with 0.5% (16.79 g kg⁻¹). In plants with six productive branches, the 1.0% dose resulted in the highest value of 20.22 g kg⁻¹, while the 0.5% dose yielded the lowest value of 15.65 g kg⁻¹. Plants with nine branches had higher potassium contents, at 1.0%, 2.0%, and 1.5%, corresponding to 21.03, 20.63, and 20.44 g kg⁻¹, respectively, and were statistically equal. The lowest value was obtained in the control plants (16.33 g kg⁻¹) (Fig. 5D).

The highest calcium content in fig trees with three branches was observed at 1.0% and 2.0%, with values of 12.25 and 12.08 g kg⁻¹, respectively, and were statistically equal; the lowest value was obtained at 0.5%, with 10.71 g kg⁻¹. In fig trees with six branches, the highest value was obtained with 2.0% of 13.67 g kg⁻¹, and the control plants had the lowest value of 10.58 g kg⁻¹. In plants with nine branches, the highest calcium content was verified using 1.5% with 12.69 g kg⁻¹, and the lowest value was obtained with 1.0% potassium silicate (Fig. 5E).

The highest magnesium contents were obtained at 2.0% and 1.5% (4.53 and 4.27 g kg⁻¹, respectively), which were statistically equivalent; the other doses did not differ significantly. Fig trees with six branches and a 1.0% dose resulted in lower magnesium contents (3.52 g kg⁻¹), while the other doses were higher and statistically equivalent. Plants with nine productive branches presented the highest magnesium content at 1.5% (4.44 g kg⁻¹), and the lowest value was obtained at a dose of 1.0% (3.50 g kg⁻¹) (Fig. 5F).

Regarding the studied micronutrient contents, it was found that fig trees with three productive branches had higher iron content than control plants (215.13 mg kg⁻¹) and those treated with 0.5% potassium silicate (214.56 mg kg⁻¹), which were statistically equal. In plants with six branches, the highest iron content was obtained in the control plants (255.41 mg kg⁻¹), and the lowest value was found at a dose of 2.0% (112.15 mg kg⁻¹). In plants with nine productive branches, the highest iron content was observed at a 0.5% dose (335.73 mg kg⁻¹); the other doses resulted in lower values (Fig. 6A).

The highest manganese content was 2.0% potassium silicate (49.36 mg kg⁻¹), and the lowest was at the 1.0%

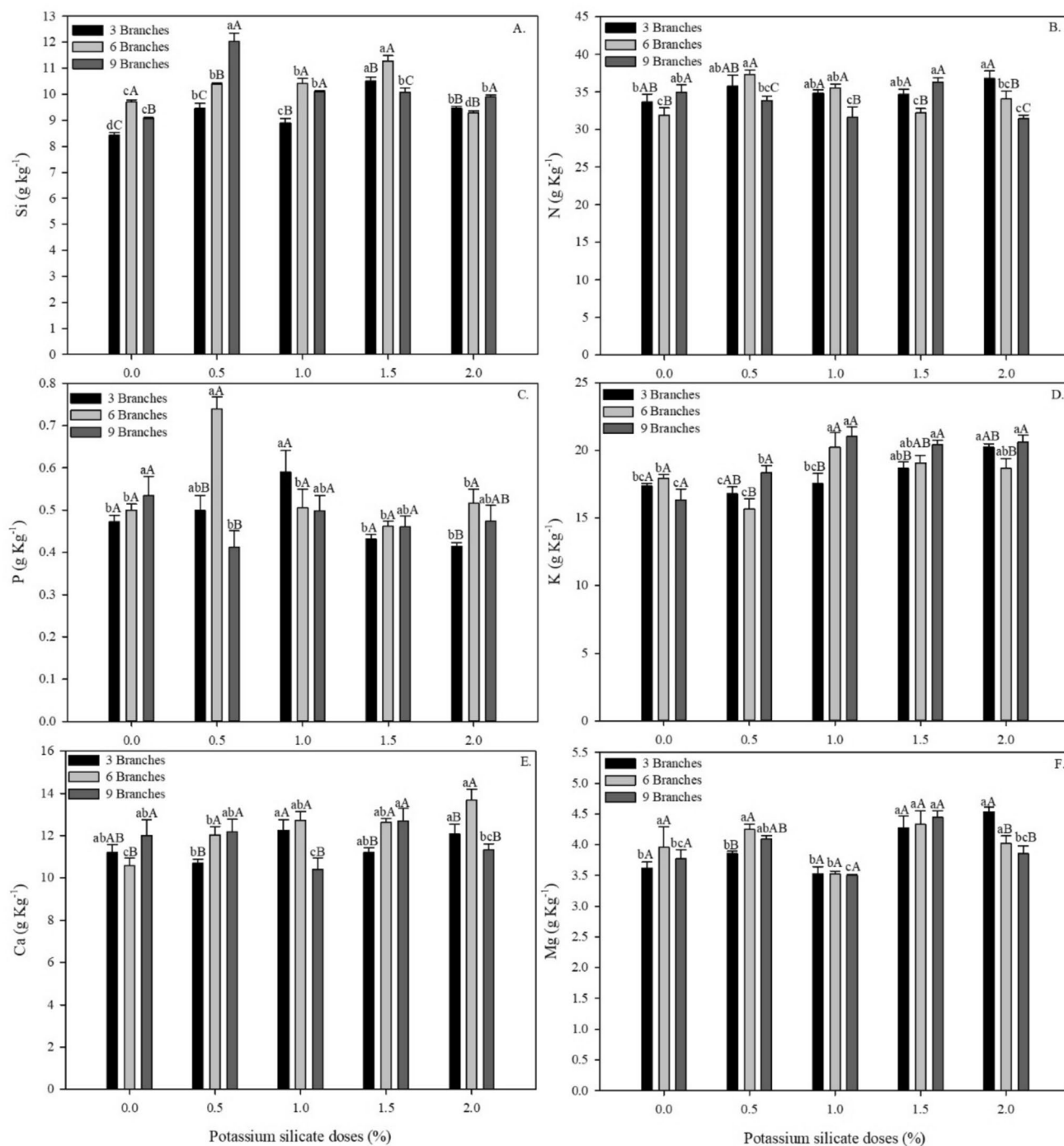


Fig. 5 Silicon (Si) (A), nitrogen (N) (B), phosphorus (P) (C), potassium (K) (D), calcium (Ca) (E), and magnesium (Mg) (F) contents in fig trees subjected to different doses of potassium silicate and num-

ber of productive branches. Mossoró- RN. *Averages followed by the same lowercase letter between branches and uppercase within the dose do not differ from each other by the LSD test ($p > 0.05$)

dose (34.88 mg kg^{-1}). The highest value was observed in plants with six branches at the 2.0% dose (62.16 mg kg^{-1}), while the lowest value was found in the control plants. In fig trees with nine branches, the highest manganese content was obtained at the 0.5% dose (45.07 mg kg^{-1}) and the lowest at the 1.0% dose (Fig. 6B). Fig trees with three

productive branches showed no significant difference in yield between the applied doses. Plants with six productive branches showed the highest zinc content (23.40 mg kg^{-1}), and the lowest contents were found at the 1.5% dose and in the control, which were statistically equal. In plants with nine productive branches, the dose of 1.5%

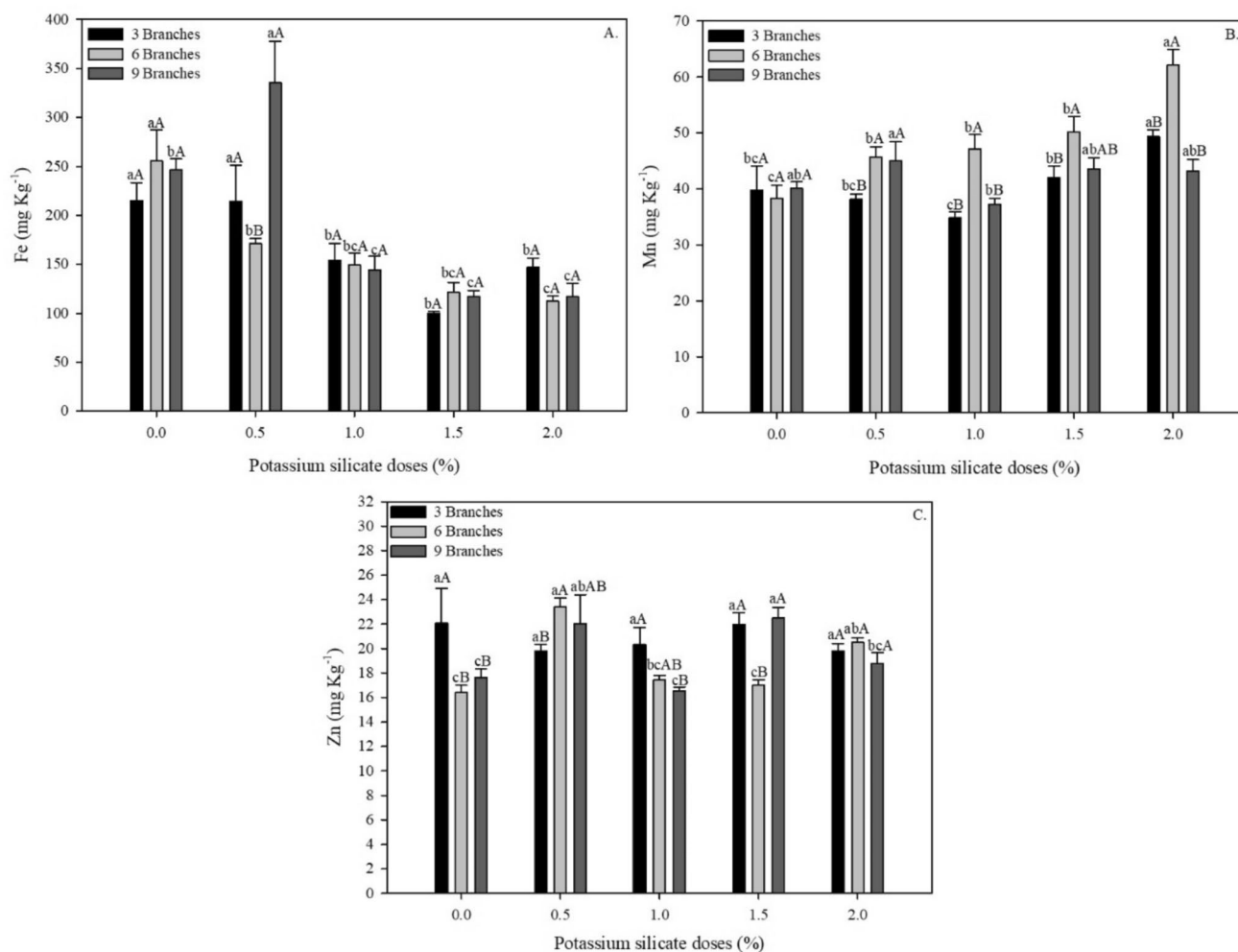


Fig. 6 Iron (Fe) (A), manganese (Mn) (B), and zinc (Zn) (C) contents in fig trees are subjected to different doses of potassium silicate and a number of productive branches. Mossoró—RN. *Averages followed

by the same lowercase letter between branches and uppercase within the dose do not differ from each other by the LSD test ($p > 0.05$)

corresponded to the highest value (22.49 mg kg⁻¹), and the lowest zinc levels were obtained in the control plants and at the dose of 1.0%, statistically equal (Fig. 6C).

4 Discussion

In this study, it was observed that fig trees benefited significantly from the applications of potassium silicate, with emphasis on the 0.5% dose, which provided a high yield of 22.00 t ha⁻¹, representing increases of 59.91% in productivity and an accumulation of 49.08% of dry matter in the aerial part of the plants. This substantial increase in productivity and biomass is not linked to a significant rise in instantaneous net photosynthetic rate (A_N), but rather to the structural and protective benefits of silicon accumulation in the plant tissue, coupled with the maintenance of the maximum

quantum efficiency of PSII (F_v/F_m) (Fig. 4). Silicon deposition enhances leaf rigidity and architecture, improving light interception and protecting the photosynthetic apparatus, thereby sustaining overall carbon assimilation throughout the growing cycle, which is fundamental for high biomass accumulation [32]. According to the FAO [33], the results of this study exceeded the national fig production in 2022 (18.22 t).

The significant accumulation of silicon in fig tree tissues (Fig. 5A), is a key factor supporting the observed gains in productivity and biomass. The deposition of Si in epidermal cells forms a physical barrier that not only increases leaf rigidity (improving light interception and canopy architecture) but also confers greater tolerance to biotic and abiotic stresses inherent to the semi-arid environment. This structural and biochemical protection is fundamental to mitigating photochemical damage and maintaining the optimal

functionality of the photosynthetic apparatus throughout the growing cycle [32, 34].

The effect of potassium silicate on plant productivity may vary according to abiotic conditions and the different susceptibilities of each species to the supply of this element in foliar form [35]. Our results confirm those of some studies that have obtained increased yields with the application of different forms of silicon in various species, such as apple trees [35–37], fig trees [38], pumpkin [39], peach trees [40], sorghum [41], and corn [42].

However, the mechanism by which this element enhances plant productivity remains uncertain. The gains in productivity are associated with changes in metabolic activity such as photosynthesis and respiration, as well as the optimization of the supply, use, and absorption of nutrients by plants, resulting in increases in mass and number of fruits, whether under normal conditions or conditions of biotic or abiotic stress [35, 43].

The increase in biomass accumulation after potassium silicate application can be attributed to several factors, including the role of Si at different points in the plant, such as improved synergistic effect on N availability and absorption. Plants that received potassium silicate applications showed greater accumulation of this nutrient, resulting in a synergistic effect that increased plant growth [44] and leaf erection. Consequently, the photosynthetic activity of plants treated with potassium silicate applications is maintained [45].

In addition to the effect of potassium silicate, plants with nine productive branches exhibited more significant biomass accumulation, possibly due to their greater number of branches and larger leaf area, resulting in increased water and nutrient storage [1]. However, as reported, using three and six branches did not differ statistically, with similar biomass production. Therefore, it is speculated that fig trees with three branches may have produced thicker branches with a greater number of leaves due to the greater availability of nutrients and photoassimilates produced. Although plants with six branches had a numerically greater number of branches, due to the division of available resources, they may have produced branches with smaller diameters and fewer leaves, which is why they presented similar biomass values.

The improvements caused in biomass and productivity are reflected in the leaf gas exchange of fig trees. This study found that applying potassium silicate at 0.5%, 1.5%, and 2.0% increased photosynthesis in fig trees, with 6 and 9 productive branches, respectively, except for three productive branches that benefited from a 1.0% dose. The increase in net photosynthesis may have occurred because silicon (Si) benefits leaf structure by promoting silica deposition in trichomes, thereby increasing light interception and absorption [46, 47].

The more significant accumulation of silica caused by potassium silicate applications, except at the 1.0% dose, in plants with nine productive branches may have resulted in multicellular deposits (silica skeletons), thereby improving leaf architecture and reducing self-shading [48]. This fact is significant in fig trees, as self-shading prevents vegetative buds from transforming into reproductive buds, reducing the plant's total photosynthesis. Shaded leaves have a lower photosynthetic rate, consequently contributing less or negatively to plant production [3–5]. As shown, even under conditions with more branches and, consequently, leaves, silicate applications improved leaf positioning relative to solar interception, which may be closely related to gains in biomass and plant productivity.

Plants treated with potassium silicate exhibited a higher transpiration rate, consistent with the stomatal conductances measured. This finding suggests that a more significant stomatal opening, linked to greater transpiration, may indicate increased gas exchange. Leaves are closely tied to the environment, particularly in relation to CO₂, the primary ingredient for photosynthesis [23, 49]. In addition, these plants exhibited increased growth and biomass, which could lead to higher soil water consumption due to greater leaf area expansion and, consequently, higher transpiration rates [45].

Plants with three productive branches showed greater *Ci* accumulation with potassium silicate applications, regardless of *gs* values. Reflecting lower values for instantaneous carboxylation efficiency than control plants. *Ci* accumulations in the mesophyll reflect adverse effects on net photosynthesis, considering that the substrate was available but could not enter the Calvin cycle [50]. However, there was no total limitation in the availability of CO₂ for the photosynthetic process, as reflected in the low *A_N* values obtained in plants with three productive branches.

Plants with six and nine branches exhibited different behaviors compared to the previous condition, specifically in the six-branch condition. The higher dose did not result in *Ci* accumulation and, consequently, greater efficiency (*A_N*/*Ci*), and under nine branches, the positive effects on *Ci* did not occur only with 2% but also extended to doses of 0.5% and 1.5%, also providing greater efficiencies (*A_N*/*Ci*). Therefore, the application of potassium silicate optimized the use of the substrate for photosynthesis, as evidenced by the high *A_N* values observed in fig trees subjected to these doses, compared to the 1% dose with six and nine productive branches.

Although the photosynthetic pigments, chlorophyll *a*, *b*, and total, were not significantly influenced by the factors studied, plants receiving the Si doses, except the 1.0% dose, had slightly higher values for chlorophyll *a*, *b*, and total than the control plants. Therefore, Si also positively affects chlorophyll pigments, thereby improving growth and production in fig trees [39].

Si increases the content of photosynthetic pigments, the basal quantum yield, and the maximum photochemical efficiency of photosystem II [51]. The maximum quantum efficiency values of PSII ranged from 0.76 to 0.79. This variable reflects the relative efficiency of light energy absorption by the PSII antenna complex and its subsequent conversion into chemical energy [52]. Therefore, at the 0.5% dose, under the conditions of three and nine branches, there was an increase in the quantum efficiency of photosystem II, possibly enabling better biomass production and plant growth.

Under the condition of six branches with the addition of the 1.5% and 2.0% doses, there was a reduction in F_v/F_m , which may be associated with the decrease in the efficiency of energy transfer from the antenna to the reaction centers and/or inactivation of the PSII reaction centers. However, it should be emphasized that this reduction did not affect photosynthesis, as it led to high A_N values [53]. The optimal average values for healthy plants vary by species; however, F_v/F_m values between 0.75 and 0.85 suggest that the photosynthetic apparatus is intact [51, 52]. In fig trees, some studies report a wide range of variations, from 0.53 to 0.93, depending on the variety and biotic and abiotic conditions [36, 51].

Because of these findings, we emphasize that there is still much to be explored regarding the responses of fig trees to the applied doses of potassium silicate and pruning management. The need for more in-depth studies exploring the definition of the most efficient source and application method, as well as explaining how this compound works in fig trees, stands out. This need for research persists in scenarios associated with other management methods and under stress conditions. It is worth noting that, regardless of the number of productive branches used, potassium silicate applications were beneficial for developing fig trees.

5 Conclusion

The application of potassium silicate, combined with pruning management, optimized the phytotechnical variables of the 'Roxo de Valinhos' fig tree under semi-arid conditions. Fig trees with six productive branches, treated with 0.5% potassium silicate, showed significant improvements in leaf gas exchange, increased net photosynthesis, and, consequently, a considerable rise in nutrient accumulation, biomass, and plant productivity.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing interest The authors declare no competing interests.

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