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Impact of the Combination of Chemical and Organic Fertilization on the Growth and Yield of Pineapple under Two Shade Net Conditions

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Abstract: The use of organic sources presents itself as a viable alternative to mitigate the excessive reliance on chemical fertilizers in agricultural practices. However, in the realm of pineapple cultivation, research exploring the synergy between chemical and organic fertilizers remains scarce. In this context, the objective of this research was to evaluate the impact of the combination of chemical and organic fertilizers on the growth and yield of the MD-2 pineapple cultivar under two shade net conditions (installed 45 and 250 days after planting). The experiment was conducted in a split-plot design, with the main plot being the shade net conditions and the sub-plots the five fertilization treatments, which were applied 18 times via drip irrigation (control, 100% chemical fertilization, 50% reduced chemical fertilization, organic fertilization, and a combination of 50% chemical fertilization with organic fertilization). The results showed that the early installation of shade netting 45 days after planting decreases the growth and yield of pineapple; thus, the use of shade netting at this age is not recommended. Regarding fertilization, the combination of 50% chemical fertilization with organic fertilization showed similar growth and yield values compared to 100% conventional chemical fertilization under both shade net conditions. Furthermore, this combination presented similar nitrate and potassium values in the plant and did not negatively affect malic acid content. Therefore, the use of organic fertilizers in pineapple cultivation is a promising strategy to reduce the excessive use of chemical fertilizers, and it could also improve soil fertility.

Keywords: pineapple; integrated nutrient management; organic fertilization; shade net; malic acid

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1. Introduction

Pineapple (*Ananas comosus* L. Merr.) ranks third among the most consumed tropical fruits, following bananas and mangoes [1]. It is the most economically relevant species within the Bromeliaceae family [2]. Pineapples are characterized by their unique aroma and sweet flavor, as well as their beneficial quantities of minerals, fibers, sugars, vitamins, and volatile compounds for human health [3]. In 2022, global pineapple production reached approximately 29.36 million metric tons [4], highlighting its worldwide significance as a significant crop both economically and nutritionally.

It is noteworthy that this global production entails the use of considerable amounts of inorganic fertilizers, especially nitrogen- and potassium-based ones. Nitrogen is essential for achieving high growth rates, while potassium plays a crucial role in fruit quality [5]. The recommended amount of nitrogen in pineapple cultivation varies between 520 and 700 kg ha^{-1}, while the potassium dose ranges from 340 to 700 kg ha^{-1} [6,7]. These requirements are strongly influenced by factors such as cultivar type, planting density, as well as the climatic conditions and soil characteristics of each region [5,7].

However, the excessive use of chemical fertilizers and phytopharmaceutical products has harmed soil health, affecting fertility and the microbiome [8–10]. A promising strategy to reduce dependence on synthetic fertilizers is the incorporation of organic amendments. Although research on this practice in pineapple cultivation is limited, approaches such as the application of vermicompost [11], green manures [12], and manure [13,14] stand out to minimize chemical fertilization. The application of organic amendments has been shown to improve synchronization between soil nutrient availability and plant uptake during pineapple's phenological stages of highest demand, thus reducing losses from leaching and volatilization [15], and has demonstrated similar or even superior yields and fruit quality compared to conventional fertilization [13,16–18]. Additionally, they increase the number of beneficial bacteria related to the carbon cycle in the rhizosphere [14].

In certain regions of pineapple cultivation, where sunlight is intense, the installation of shade netting after floral induction is common to prevent severe fruit sunburn and preserve quality [19,20]. Additionally, it has been reported that the use of shade nets increases pineapple crop productivity [21]. However, there is limited information on plant responses when shade netting is installed from the beginning of planting. Additionally, the implementation of sprinkler or drip irrigation systems in pineapple production emerges as an effective option for the precise application of soluble fertilizers, whether inorganic or organic in origin [22,23]. Despite not being commonly used due to the predominance of rainfed conditions in most pineapple-growing areas, these irrigation systems offer a viable alternative to meet crop water needs and provide nutrients efficiently [24]. Some recent studies have shown that supplementary sprinkler irrigation and drip irrigation promote increased productivity and fruit quality in pineapple [25,26]. In this context, the present research evaluates the contribution of vermicompost to the soil and the combination of chemical and organic soluble fertilizers applied through drip irrigation to the growth and yield of MD-2 pineapple under two shade netting conditions.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted from August 2019 to October 2020 at the University of Papaloapan in Loma Bonita, Oaxaca, Mexico, situated at coordinates 18°05′56.5″ N 95°53′48.8″ W and an elevation of 30 m above sea level. Temperature and precipitation data throughout the experiment (Figure 1) were sourced from the CRU TS (Climatic Research Unit gridded Time Series) version 4.05 database, utilizing Google Earth Pro. CRU TS is a comprehensive dataset of interpolated climate information derived from an extensive network of climatological stations organized on a 0.5°-latitude-by-0.5°-longitude grid across the globe, excluding Antarctica [27]. The soil at the experimental site is characterized as acidic (pH 4.5, water 1:2), with a loamy texture, and contains 2.9% organic matter (Walkley and Black), 36 mg kg^{-1} of N-NO_3^- (Kjeldahl), 62 mg kg^{-1} of P (Bray), 28 mg kg^{-1} of K, 207 mg kg^{-1} of Ca, and 119 mg kg^{-1} of Mg (ammonium acetate pH 7.0).

2.2. Experiment Design and Treatments

The experiment was conducted using a split-plot design with the MD-2 pineapple cultivar. The main plot consisted of two shade net conditions. In the first condition, black shade netting with 70% shading was installed 45 days after planting (dap), and in the second condition, black shade netting with 70% shading was installed at 250 dap. In the sub-plots, five fertigation treatments were applied. These treatments included (1) a control (water application only), (2) conventional chemical fertilization at 100% (F100), as shown in Table 1, (3) reduced conventional chemical fertilization at 50% (F50), (4) organic fertilization (vermicompost incorporated prior to planting + NUTRIPRO® Forte + NUTRIPRO® Xtra-ALGA, Ultraquimia Group, Morelos, Mexico; O), and (5) a combination of 50% chemical fertilization and organic fertilization (F50 + O). Conventional fertilization in this experiment was based on a recommendation by Uriza-Ávila et al. [28]. The plot consisted of 210 plants for each shade net condition and 42 plants in each sub-plot (fertilization treatment). This gives us a total of 420 plants in the experiment.

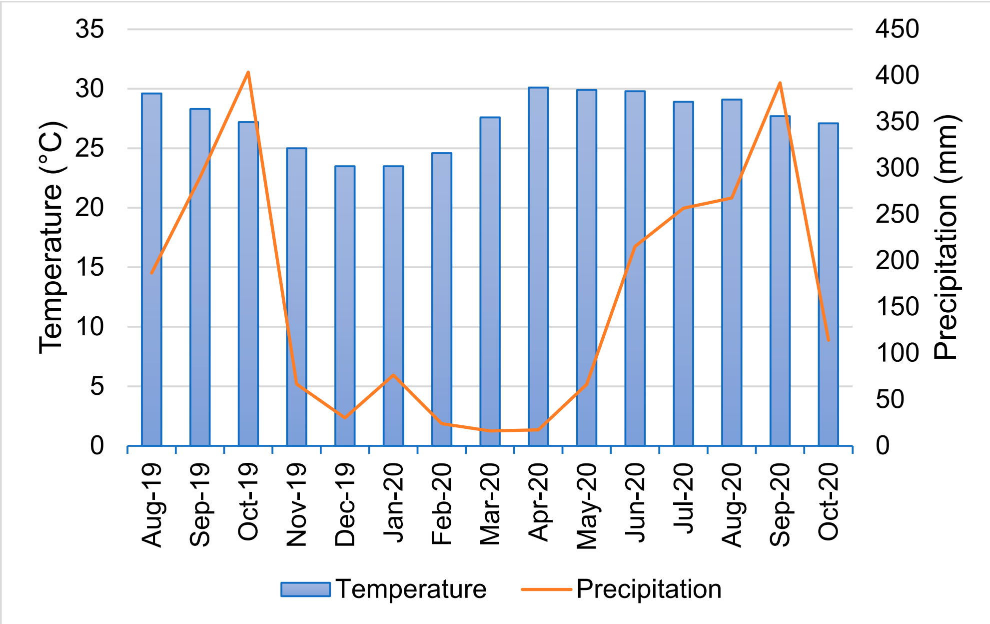

Figure 1. Temperature and precipitation during the experiment.

Table 1. Amount of nutrients applied to the F100 treatment (kg ha^{-1}) through drip irrigation.

Days after Planting	N	P_2O_5	K_2O	CaO	MgO	$SO_4{}^{2-}$
45	32.53	13.68	45.26	13.68	7.58	4.74
60	32.47	16.05	0.00	13.68	7.58	0.00
75	32.47	16.05	0.00	13.68	7.58	0.00
90	56.58	13.68	55.26	27.37	15.16	0.00
105	56.58	13.68	55.26	27.37	15.16	0.00
120	39.89	16.05	59.47	27.37	15.16	17.05
135	80.03	13.68	111.26	34.21	21.05	4.74
150	39.89	16.05	59.47	27.37	15.16	17.05
165	39.89	16.05	59.47	27.37	15.16	17.05
180	29.92	13.68	65.79	6.84	8.42	14.21
195	23.87	6.84	29.21	10.26	8.42	11.58
210	25.13	6.84	31.05	13.68	8.42	10.16
225	22.16	4.11	28.21	10.26	8.42	13.95
255	24.13	6.84	30.00	13.68	8.42	13.95
270	24.13	6.84	30.00	13.68	8.42	13.95
300	25.53	6.84	42.37	6.84	4.21	12.89
330	25.53	6.84	42.37	6.84	4.21	12.89
360	25.53	6.84	42.37	6.84	4.21	12.89
Grand total	636.26	200.64	786.82	301.02	182.74	177.1

The experiment was established in ridges of 40 cm width with a spacing of 70 cm between ridges. Vermicompost (10 t ha^{-1} applied only to treatments O and F50 + O) was incorporated on top of the ridges, and Toro® drip tape (self-compensating dripper, 6000-gauge, 16 mm diameter, emitter spacing every 30 cm, The Toro Company, Bloomington, MN, United States) was installed. Subsequently, silver/black plastic mulch with a gauge of 90 was placed on each ridge, with the black side facing down and the silver side facing up. On 30 August 2019, planting was carried out on both sides of the ridge, leaving a 20 cm spacing between rows and 30 cm between plants. Plants were pruned before planting to an approximate height of 30 cm. The planting density was 60,000 plants per hectare. Ten days after planting, Rootex® (a combination of phytohormones, amino acids, organic acids, and nutrients) was applied at a rate of 2 kg ha^{-1} to promote root growth. Weed control was performed manually, and other management practices were based on local agronomic practices.

2.3. Sources of Applied Fertilizers

The vermicompost applied in this study was locally produced. It contained 16.7% organic matter, 9.7% organic carbon (calcination method), and 0.57% N (Dumas method). Additionally, it contained 0.35, 0.24, 0.81, and 0.29% P, K, Ca, and Mg, respectively (determined by microwave digestion/ICP). The pH level was 6.4. The sources of liquid organic fertilizer were NUTRIPRO® Forte (1.7% N, 0.98% P, 1.8% K, and 3.24% organic matter) and NUTRIPRO® Xtra-ALGA (1.12% N, 0.82% P, 5.66% K, and 1.22% total amino acids) at a concentration of 1 mL L^{-1} each. These organic fertilizers provided 91 kg ha^{-1} of N, 58 kg ha^{-1} of P, and 240 kg ha^{-1} of K to treatments O and F50 + O. Conventional chemical fertilizer doses were formulated using urea, calcium nitrate, magnesium nitrate, potassium nitrate, magnesium sulfate, potassium sulfate, and monopotassium phosphate. Additionally, five micronutrient applications were carried out 90, 105, 180, 255, and 300 days after planting (dap) using Ultrasol® MicroMix (Fe-EDTA 7.5%, Mn-EDTA 3.7%, B 0.4%, Zn-EDTA 0.6%, Cu-EDTA 0.3%, and Mo 0.2%) at a concentration of 0.1 g L^{-1}. Throughout the experiment, the fertilization treatments were applied 18 times, with an application volume of 125 L per fertilization treatment in each irrigation. This volume is sufficient to wet a depth of 40 cm, where most of the roots are located.

2.4. Floral Induction

Floral induction (from 245 dap) was carried out based on the methodology described by Bonomo et al. [23]. Briefly, the water pH was adjusted to 9.0 with NaOH. Then, Ethrel® (2-chloroethyl phosphonic acid) was prepared at a dose of 1.5 mL L^{-1}, mixed with 1.3 g L^{-1} of urea and ice, and applied directly to the plant's apex (50 mL) using a manual sprayer during the cooler morning hours on 1, 3 and 5 May 2020.

2.5. Measured Parameters

At 180 dap, the number of leaves and the length and width of leaf D were measured for twenty plants from each treatment. The D leaf is the tallest; it has non-chlorophyll tissue and is easy to detach. It is used as an index of plant growth and nutritional status. It is identified by grouping the tallest leaves and then selecting the one that stands out from the others [5]. Additionally, leaf area was calculated using the length and width of leaf D with the regression equation determined by Dos Santos et al. [29]. At 450 dap, the fresh weight was measured for three plants from each treatment using an electronic scale (Rhino® model BAPRE-3, RHINO, Mexico city, Mexico). The yield per plant was determined from the average weight of 42 fruits from each treatment.

Malic acid determination was carried out according to the methodology of Gómez-Herrera et al. [30] at 210 dap. At dusk (6 pm), three leaf D samples from each treatment were collected, and the cellular content was extracted by grinding 3 g with 20 mL of distilled water in a mortar. The extract was then centrifuged at 1000 rpm for 5 min at room temperature (Science Med®, DM0412S, Science-Med Laboratory Instruments Limited, Helsinki, Finland). The supernatant was adjusted to 30 mL with distilled water and titrated with 0.1 N NaOH until a persistent pink coloration was obtained. The results were expressed in mg of malic acid/100 g of leaf fresh weight.

To measure the ions (nitrate, potassium, and calcium) and total soluble solids, three leaf D samples and three fruits from each treatment were used. Subsequently, approximately 0.5 cm of the basal part of leaf D (white tissue) was cut [5], and then 1 mL of sap was extracted using a manual hydraulic press [31], while 1 mL of juice was manually extracted from ripe fruits (88–100% yellow peel). The ions were then measured using LAQUAtwin®

portable meters (Horiba, Kyoto, Japan), previously calibrated with the manufacturer's solution. Total soluble solids were measured with a digital refractometer (HI 96801 Hanna Instruments®, Woonsocket, RI, USA). Additionally, 10 mL of fruit juice was extracted, and the pH was measured using a digital pH meter (HI 98130 Hanna Instruments®, Woonsocket, RI, USA). Subsequently, the titratable acidity of the fruits was determined with 0.1 N sodium hydroxide until a persistent pink coloration was obtained [32], and the results were expressed as a percentage of citric acid.

2.6. Statistical Analysis

A two-way analysis of variance (ANOVA) and Fisher's LSD mean comparison test ($p \leq 0.05$) were applied to all evaluated variables. Statistical analyses were conducted using the INFOSTAT statistical software, version 2020.

3. Results

3.1. Leaf D Growth, Biomass, and Yield

Both shade net conditions and fertilization treatments had a significant effect on leaf D growth, plant fresh biomass, and yield (Table 2). Concerning the shade net conditions, the shade net installed at 45 days after planting (dap) significantly reduced the leaf D width, leaf number, leaf area, plant fresh weight, and yield (by 16, 15, 8, 41, and 20%, respectively). Conversely, it increased the leaf D length by 15%. This clearly shows that the leaves shaded at 45 dap were etiolated. Regarding fertilization, both 100% chemical fertilization (F100) and the combination of 50% chemical fertilization and organic fertilization (F50 + O) significantly increased the leaf D length and width, leaf number, leaf area, plant fresh weight, and pineapple yield compared to simple 50% chemical fertilization (F50), simple organic fertilization (O), and the control (Table 2).

Table 2. Effects of fertilization treatments and shade netting on pineapple growth, biomass, and yield.

	Leaf D Length (cm)	Leaf D Width (cm)	Number of Leaves	Leaf D Leaf Area (cm^2)	Plant Fresh Weight (g)	Yield per Plant (g)
Shade Netting (SN)						
250 dap	74.5 b	6.27 a	34.0 a	470 a	3049 a	1881 a
45 dap	86.0 a	5.27 b	28.7 b	430 b	1784 b	1504 b
Fertilization (F)						
Control	72.9 d	4.76 c	22.0 e	353 c	1976 cd	1439 d
O	72.3 d	4.86 c	26.5 d	358 c	1737 d	1564 c
F50	79.5 c	5.93 b	33.5 c	459 b	2658 b	1719 b
F50 + O	85.7 b	6.66 a	36.0 b	531 a	2403 bc	1841 a
F100	91.0 a	6.65 a	38.8 a	547 a	3303 a	1900 a
ANOVA significance						
SN	***	***	***	***	***	***
F	***	***	***	***	**	***
SN × F	***	***	***	***	*	**

* $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$. dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between columns indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

As shown in Table 2, the interaction between the fertilization treatments and the two shade net conditions had a significant effect on the leaf D growth, plant fresh biomass, and yield. Compared to the control and simple organic fertilization, treatments F100 and F50 + O increased in terms of the leaf D width, leaf area, leaf number, and yield per plant under both shade net conditions (45 and 250 dap), as shown in Figure 2B, Figure 2C, Figure 2D, and Figure 2F, respectively. Additionally, treatment F100 increased the leaf D length (Figure 2A) and plant fresh weight (Figure 2E) under both shade net conditions, while treatment F50 + O only increased the leaf length when the shade net was installed at 250 dap.

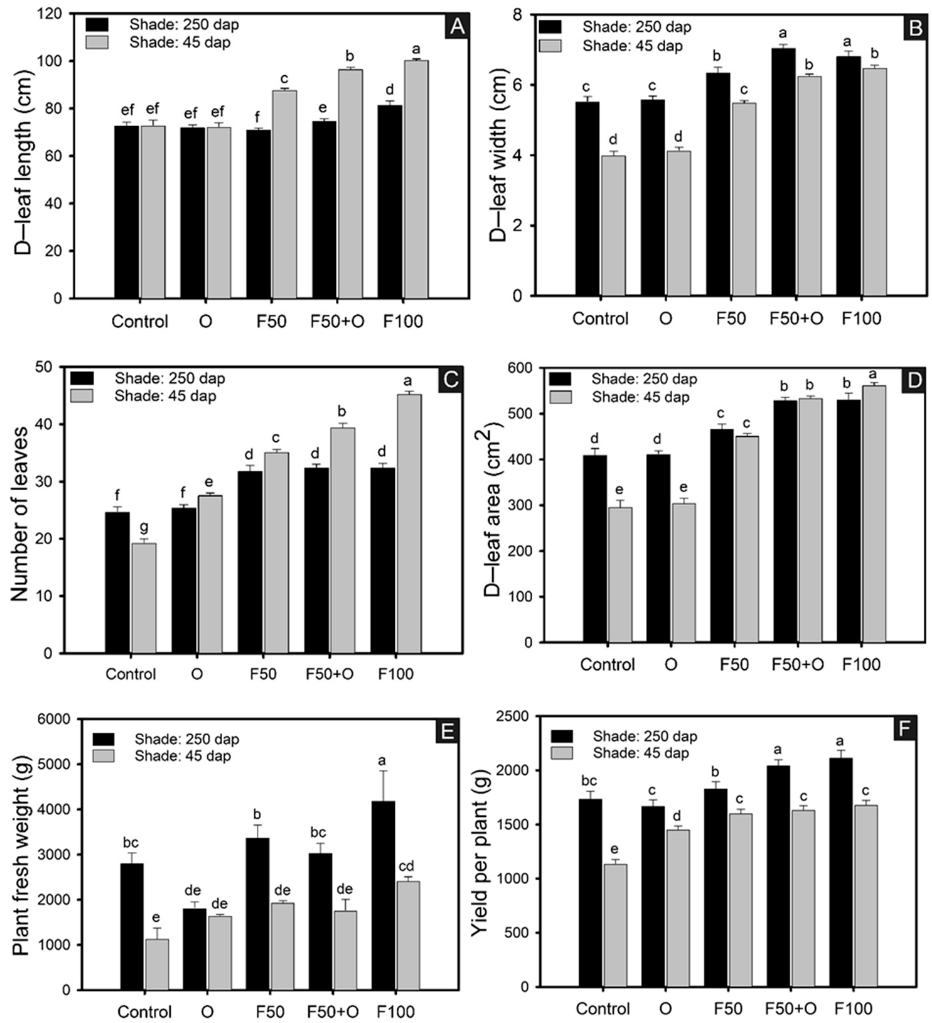

Figure 2. Interaction effect between fertilization and shade net conditions on leaf length (**A**) and width (**B**), number of leaves (**C**), leaf area (**D**), plant fresh weight (**E**), and yield (**F**). dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between bars indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

3.2. Malic Acid, Total Soluble Solids, and Nutrients in the Leaves

The shade net conditions and fertilization treatments significantly modified the malic acid content, total soluble solids, and leaf D nutrients (Table 3). Regarding the shade netting, the shade net installed at 45 dap showed a higher malic acid content (424%) and a lower total soluble solids content (24%). Conversely, the shade net installed at 250 dap increased the nitrate and calcium contents (85 and 56%, respectively). Potassium was not affected by the shade net conditions. As for fertilization, treatments F100 and F50 + O increased the malic acid content compared to treatments F50 and O and the control; these treatments also showed a higher potassium content than the control. Additionally, treatment F100 showed higher nitrate values than treatment O and the control.

In terms of interaction, significant differences were only observed for malic acid and calcium (Table 3). Treatments F100 and F50 + O showed the highest values of malic acid when the shade net was placed at 250 dap; whereas when the shade net was installed at 45 dap, they did not show significant differences (Figure 3A). Regarding the calcium content, the control exhibited the highest value compared to treatment O at 250 dap and compared to treatments F5O and F100 at 45 dap, as shown in Figure 3B.

Table 3. Effects of fertilization treatments and shade netting on malic acid, total soluble solids, and nutrients in leaf D.

	Malic Acid (mg/100 g FW)	Total Soluble Solids (°Brix)	$N\text{-}NO_3^-$ ($mg\ L^{-1}$)	K+ ($mg\ L^{-1}$)	Ca^{2+} ($mg\ L^{-1}$)
Shade Net (SN)					
250 dap	1.25 b	1.75 a	2376 a	1177	310 a
45 dap	6.56 a	1.33 b	1284 b	1068	198 b
Fertilization (F)					
Control	3.31 c	1.42	1421 b	711 b	331
O	4.36 b	1.43	1366 b	1013 ab	243
F50	0.97 d	1.53	1983 ab	1140 ab	243
F50 + O	5.25 a	1.47	1980 ab	1283 a	246
F100	5.62 a	1.83	2400 a	1466 a	206
ANOVA significance					
SN	***	**	***	ns	***
F	***	ns	**	*	ns
SN × F	***	ns	ns	ns	*

ns $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$. dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between columns indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

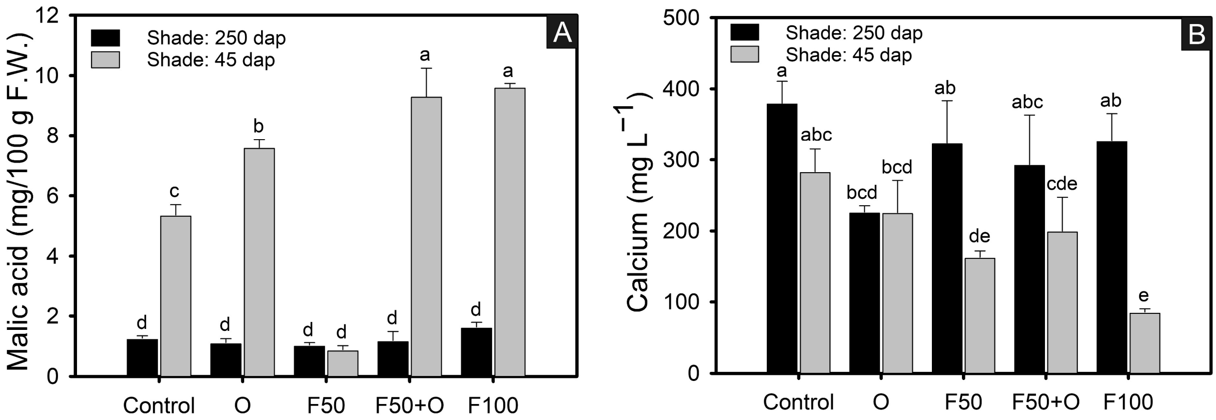

Figure 3. Interaction effect between fertilization and shade net conditions on malic acid (**A**) and calcium (**B**). dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between bars indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

3.3. Nutrients, pH, Titratable Acidity, and Total Soluble Solids in the Fruits

The shade net conditions and fertilization treatments showed significant differences in terms of the nutrients, pH, titratable acidity, and total soluble solids of the fruits (Table 4). Regarding shade net conditions, the shade net installed at 250 dap increased the nitrate and potassium contents, as well as the pH and titratable acidity of the fruits (11, 9, 10, and 29%, respectively). In contrast, the shade net installed at 45 dap increased the calcium content and total soluble solids content of the fruits (35% and 4%, respectively). Concerning fertilization, treatments F50 + O and F100 increased the nitrate and potassium contents of the fruits compared to the control. Conversely, treatments F50 + O and F100 showed the lowest percentage of titratable acidity compared to treatment F50 and the control. However, treatment F100 showed higher values of total soluble solids than F50 + O. On the other hand, the control showed the highest values of calcium and pH compared to the other treatments.

Regarding interaction, the control and organic treatment exhibited the highest values of calcium when the shade net was installed at 45 dap (Figure 4A). Conversely, treatment F100 showed the lowest values of pH and titratable acidity (Figure 4B,C) under both shade net conditions and presented the highest value of total soluble solids (Figure 4D) when the shade net was installed at 250 dap.

Table 4. Effects of fertilization treatments and shade netting on nutrients and fruit quality of pineapple.

	N-NO_3^- (mg L^{-1})	**K^+ (mg L^{-1})**	**Ca^{2+} (mg L^{-1})**	**pH**	**Titratable Acidity (% Citric Acid)**	**Total Soluble Solids (°Brix)**
Shade Net (SN)						
250 dap	145 a	1037 a	18.4 b	3.63 a	1.37 a	14.8 b
45 dap	130 b	948 b	24.8 a	3.53 b	1.06 b	15.5 a
Fertilization (F)						
Control	96 c	701 d	39.5 a	3.94 a	1.34 b	15.2 abc
O	141 b	880 c	29.5 b	3.92 ab	1.09 c	15.5 ab
F50	158 a	1028 b	16.7 c	3.79 c	1.52 a	14.8 bc
F50 + O	158 a	1255 a	11.0 d	3.84 bc	1.08 c	14.6 c
F100	134 b	1097 b	11.5 d	2.42 d	1.02 c	15.5 a
ANOVA significance						
SN	**	*	***	***	***	**
F	***	***	***	***	***	*
SN × F	ns	ns	***	**	***	**

ns $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$. dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between columns indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

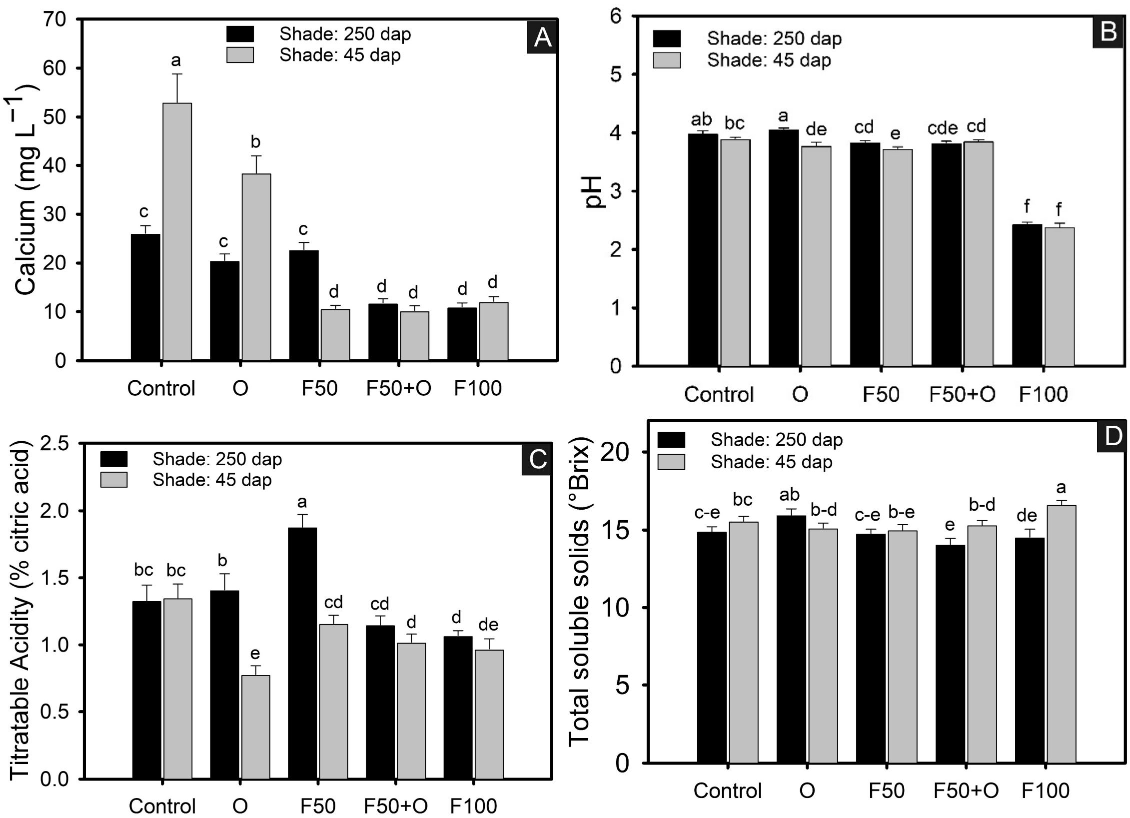

Figure 4. Interaction effect between fertilization and shade net conditions on calcium (**A**), pH (**B**), titratable acidity (**C**), and total soluble solids (**D**). dap: days after planting; O: organic. F50: fertilization at 50%. F50 + O: fertilization at 50% and organic. F100: fertilization at 100%. Different lowercase letters between bars indicate a significant difference according to the Fisher LSD test ($p \leq 0.05$).

4. Discussion

The use of shade netting in pineapple cultivation to protect fruits from sunburn due to high radiation and improve yield has been reported [19–21]. However, there are few studies reporting on the effect of shading or a lack of light [33] from planting to harvest. This research demonstrated that shade netting installed at 45 days after planting (dap) resulted in a decrease in pineapple growth and yield, as well as a reduction in total soluble solids, nitrate, and calcium in leaf sap. Pineapple is a bromeliad with constitutive crassulacean acid metabolism (CAM), where malate is the most important anion for carbon fixation [34]. During the night, when the stomata open, the phosphoenolpyruvate carboxylase enzyme carboxylates phosphoenolpyruvate into oxaloacetate (OAA); then, OAA is reduced to malate-by-malate dehydrogenase enzymes, accumulating in the vacuole as malic acid. During the day, malic acid moves to the cytoplasm and is decarboxylated by malic enzymes or phosphoenolpyruvate carboxykinase enzymes, and CO_2 is mostly converted to hexoses through the Calvin cycle or gluconeogenesis pathway [34,35]. However, under favorable environmental conditions such as a suitable temperature, humidity (both soil and air), and light intensity, pineapple can easily switch its metabolism to facultative C3/CAM [36,37]. Light intensity is a determining factor, as demonstrated when the pineapple plants were subjected to the C3 (40 µmol m^{-2} s^{-1}) or CAM (260 µmol m^{-2} s^{-1}) conditions; the C3 plants showed a lower leaf thickness, leaf area, fresh and dry weight, net photosynthesis rate, and sucrose content [33], which is consistent with our results. We propose that the shade net placed at an early age (45 dap) reduced light intensity, leading to a modification of constitutive metabolism to facultative and consequently reducing growth and yield. Additionally, the plants under shade net conditions at 45 dap showed higher malic acid content at sunset, which may be attributed to a small portion of the CO_2 taken in during the day being stored as malic acid in the vacuole due to facultative C3/CAM metabolism [37].

In pineapple cultivation, the combination of organic fertilizers with chemical fertilizers is a promising strategy for reducing the use of chemical fertilizers. In this study, it has been demonstrated that the combination of 50% chemical fertilization and organic fertilization (F50 + O), as well as 100% chemical fertilization (F100), outperformed 50% chemical fertilization (F50), organic fertilization (O), and the control in terms of the growth (length and width of D leaf, leaf area, and number of leaves) and yield of the MD-2 pineapple cultivar (Table 2). When analyzing the interaction with shade netting, it is observed that these treatments (F100 and F50 + O) maintain the same trend under both shade net conditions (Figure 2). This finding suggests that incorporating vermicompost into the soil before planting and applying organic fertilizers through drip irrigation can reduce the need for applying 50% chemical fertilizers without negatively affecting pineapple growth and yield. These effects can be attributed to the high availability of nutrients, organic matter, organic carbon, and humic acids, as well as the presence of growth regulators such as cytokinins and auxins in the vermicompost [38]. Another plausible explanation is that both inorganic and organic fertilizers were applied through drip irrigation, considered the most efficient method for nutrient application in crops [39], and pineapple cultivation is no exception [23]. Similar results to ours have been reported by Darnaudery et al. [12], who demonstrated that integrated fertilization, including green manure and chemical fertilization, produced pineapple fruit weights comparable to conventional fertilization, while simple organic fertilization showed the lowest fruit weights. Other studies also indicate that the partial substitution of traditional chemical fertilization (20% of N) with organic fertilization increases pineapple yield compared to conventional fertilization [13,16,17]. Additionally, Mahmud et al. [11] reported that the number of leaves and the length and width of the D leaf were similar with the individual application of vermicompost or chemical fertilizer, but chemical fertilization showed a higher yield than organic fertilization.

In this research, it was also demonstrated that treatments F100 and F50 + O showed similar values of nitrate and potassium in the sap of leaf D (Table 3). This evidence indicates that two essential nutrients (N and K), required in large quantities by pineapple crops, were not negatively affected by the combination of chemical and organic fertilization. Therefore, the joint use of chemical and organic fertilizers emerges as a promising option in pineapple cultivation, as organic fertilization increases carbon and nitrogen content, thus improving soil fertility and supplying nutrients (N and K) at the precise moment for absorption by the plant [40]. This finding aligns with that of Rothé et al. [15], who conclude that composted fertilizers, combined with green manure, create adequate synchronization between nitrogen release and pineapple plant absorption during the vegetative phase. Additionally, Jin et al. [16] point out that the combination of inorganic and organic fertilization improves the availability of nitrate and potassium in soils intended for pineapple cultivation. Likewise, Cai et al. [13] demonstrated that replacing 20% of conventional N with an organic fertilizer (sheep manure) increased N absorption in pineapple plants. In other crops, such as sunflower [41], maize [42], and rice [43], it has been proven that the partial substitution of chemical fertilizers with organic fertilizers enhances the soil structure and available nitrogen, leading to higher crop yields.

Something peculiar happened with calcium, as the interaction analysis showed that treatments F100 and F50 significantly decreased the calcium content in the D leaves of the plants under shade netting at 45 dap (Figure 3). Similarly, in the fruits, treatments F100 and F50 + O significantly reduced the calcium content compared to the control under both shade net conditions (Figure 4). This could be attributed to the high rates of application of NPK chemical fertilizers, which reduced the availability of calcium ions in the soil, as demonstrated by Wan et al. [44] in ferric acrisol and fluvic cambisol soils. However, this reduction in calcium in leaves and fruits (F100 and F50 + O) did not negatively affect the pineapple yield.

Regarding malic acid in leaf D, it was observed that treatments F100 and F50 + O showed the highest values compared to treatments F50 and O and the control (Table 3). Additionally, the interaction analysis revealed that these treatments maintained this trend when the shade net was installed at 45 dap. As mentioned earlier, malate is the most important anion for carbon fixation in constitutive CAM metabolism [34]. Therefore, the accumulation of malic acid in the vacuoles of leaf D was not negatively affected by the combination of inorganic and organic fertilizers, as they presented similar values to conventional fertilization. This allowed for promoting better growth and yield in pineapple cultivation.

Concerning fruit, the combination of chemical and organic fertilization increased the nitrate and potassium content in the fruits compared to F100, although both treatments were superior to the control. This demonstrates that there was good transportation of nitrate and potassium from the leaves (source) to the fruits (sink). Nitrogen and potassium play an important role in the quality of pineapple fruits, as they regulate the formation of sugars and organic acids [45]. Additionally, it was shown that the F100 treatment had a higher total soluble solids content than the F50 + O treatment; the same trend occurred when the shade net was placed 45 days after planting. This is likely due to the amount of potassium contained in the F100 treatment, which aligns with what other authors have reported, that as the dose of potassium fertilization increases, the total soluble solids also increase [45,46]. However, the F100 treatment showed similar values of soluble solids to the control, which coincides with the results reported by other authors [11,12]. It is worth noting that the soluble solids values presented by the fruits of the different evaluated treatments are within the minimum required (12 °Brix) by the CODEX ALIMENTARIUS [47]. Unlike other studies that report that as the pH decreases, the titratable acidity of the fruit increases, or vice versa [48,49], here we report that treatments F100 and F50 + O showed a decrease in both the pH and titratable acidity of the fruits under both shade net conditions, which could be attributed to the high availability of nitrogen included in the treatments. These results are consistent with another study, where they reported that as the rate of nitrogen fertilization in pineapple cultivation increases, the titratable acidity (% citric acid) of the fruits decreases, attributing it to a dilution of the cellular content due to the increase in fruit biomass [45]. Another hypothetical explanation is that the enzymes aconitase [50] and glutamate decarboxylase [51] probably showed higher activity than the enzyme citrate synthase; these enzymes have been reported to be responsible for the degradation of citrate in pineapple fruits.

In addition to the positive benefits evidenced in this study regarding growth and yield, the partial substitution of inorganic fertilizers with organic ones can lead to an increase in economic benefits for pineapple producers, as demonstrated in other research [11,13]. This strategy also contributes to reducing greenhouse gas emissions into the environment [13]. However, it is important to consider the high application rate and elevated unit price of organic fertilizers, such as vermicompost [11]. This could result in increased costs. Nevertheless, this aspect could improve with the future development of the organic fertilizer industry and production technology.

5. Conclusions

The installation of shade netting 45 days after planting had a negative impact on both growth and yield, so installing shade netting at that stage of pineapple cultivation is not recommended. The combination of 50% chemical fertilization with organic fertilization (F50 + O) showed similar growth and yield values in the MD-2 pineapple cultivar compared to 100% chemical fertilization under both shade net conditions. This finding suggests that the application of organic fertilizers in combination with chemical fertilizers through drip irrigation can be an effective strategy for reducing dependence on conventional chemical fertilization without compromising yield. Furthermore, the incorporation of organic fertilizers (vermicompost) can improve soil fertility, which is important in areas characterized by pineapple monocultures. These results offer valuable insights and will serve as a reference point for future research related to the combination of chemical and organic fertilizers in pineapple production.

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References

1. FAOSTAT. 2024. Available online: http://www.fao.org/faostat/en/#home (accessed on 4 May 2024).
2. Wali, N. Pineapple (*Ananas comosus*). In *Nonvitamin and Nonmineral Nutritional Supplements*; Nabavi, S.M., Silva, A.S., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 367–373.
3. Mohd Ali, M.; Hashim, N.; Abd Aziz, S.; Lasekan, O. Pineapple (*Ananas comosus*): A Comprehensive Review of Nutritional Values, Volatile Compounds, Health Benefits, and Potential Food Products. *Food Res. Int.* **2020**, *137*, 109675. [CrossRef] [PubMed]
4. Shahbandeh, M. Global Pineapple Production 2002–2022. Available online: https://www.statista.com/statistics/298505/global-pineapple-production/ (accessed on 15 February 2024).
5. Vásquez-Jiménez, J.; Bartholomew, D.P. Plant Nutrition. In *The Pineapple: Botany, Production and Uses*; CABI: Wallingford, UK, 2018; pp. 175–202.
6. Leon, R.G.; Kellon, D. Characterization of 'MD-2' planting density and fertilization using a grower survey. *Horttechnology* **2012**, *22*, 644–650. [CrossRef]
7. Rebolledo-Martínez, A.; Peralta-Antonio, N.; Rebolledo-García, R.L.; Becerril-Román, A.E.; Rebolledo-Martínez, L.; Jaén-Contreras, D.; Uriza-Ávila, D.E.; Inurreta-Aguirre, H.D.; Montiel-Vicencio, G. Nitrogen, phosphorus and potassium content in different organs of pineapple cultivars at different planting density. *Trop. Subtrop. Agroecosyst.* **2023**, *26*, 081. [CrossRef]
8. Dey, A.; Chaudhuri, P.S. Earthworm Community Structure of Pineapple (*Ananas comosus*) Plantations under Monoculture and Mixed Culture in West Tripura, India. *Trop. Ecol.* **2014**, *55*, 1–17.

9. Cornwell, E. Effects of Different Agricultural Systems on Soil Quality in Northern Limón Province, Costa Rica. *Rev. Biol. Trop.* **2014**, *62*, 887–897. [CrossRef] [PubMed]
10. Streletskii, R.; Astaykina, A.; Krasnov, G.; Gorbatov, V. Changes in Bacterial and Fungal Community of Soil under Treatment of Pesticides. *Agronomy* **2022**, *12*, 124. [CrossRef]
11. Mahmud, M.; Abdullah, R.; Yaacob, J.S. Effect of Vermicompost Amendment on Nutritional Status of Sandy Loam Soil, Growth Performance, and Yield of Pineapple (*Ananas comosus* Var. MD2) under Field Conditions. *Agronomy* **2018**, *8*, 183. [CrossRef]
12. Darnaudery, M.; Fournier, P.; Léchaudel, M. Low-input pineapple crops with high quality fruit: Promising impacts of locally integrated and organic fertilisation compared to chemical fertilisers. *Exp. Agric.* **2018**, *54*, 286–302. [CrossRef]
13. Cai, J.; Cheng, W.; Liang, Z.; Li, C.; Deng, Y.; Yin, T.; Li, C. Organic and Slow-Release Fertilizer Substitution Strategies Improved the Sustainability of Pineapple Production Systems in the Tropics. *Sustainability* **2023**, *15*, 10353. [CrossRef]
14. Chen, W.; Zhang, X.; Hu, Y.; Zhao, Y. Effects of Different Proportions of Organic Fertilizer in Place of Chemical Fertilizer on Microbial Diversity and Community Structure of Pineapple Rhizosphere Soil. *Agronomy* **2024**, *14*, 59. [CrossRef]
15. Rothé, M.; Darnaudery, M.; Thuriès, L. Organic Fertilizers, Green Manures and Mixtures of the Two Revealed Their Potential as Substitutes for Inorganic Fertilizers Used in Pineapple Cropping. *Sci. Hortic.* **2019**, *257*, 108691. [CrossRef]
16. Jin, X.; Cai, J.; Yang, S.; Li, S.; Shao, X.; Fu, C.; Li, C.; Deng, Y.; Huang, J.; Ruan, Y.; et al. Partial Substitution of Chemical Fertilizer with Organic Fertilizer and Slow-Release Fertilizer Benefits Soil Microbial Diversity and Pineapple Fruit Yield in the Tropics. *Appl. Soil Ecol.* **2023**, *189*, 104974. [CrossRef]
17. Liang, Z.; Jin, X.; Zhai, P.; Zhao, Y.; Cai, J.; Li, S.; Yang, S.; Li, C.; Li, C. Combination of Organic Fertilizer and Slow-Release Fertilizer Increases Pineapple Yields, Agronomic Efficiency and Reduces Greenhouse Gas Emissions under Reduced Fertilization Conditions in Tropical Areas. *J. Clean. Prod.* **2022**, *343*, 131054. [CrossRef]
18. Domínguez-Gento, A.; Di Giorgi, R.; García-Martínez, M.D.; Raigón, M.D. Effects of Organic and Conventional Cultivation on Composition and Characterization of Two Citrus Varieties 'Navelina' Orange and 'Clemenules' Mandarin Fruits in a Long-Term Study. *Horticulturae* **2023**, *9*, 721. [CrossRef]
19. Weifeng, Z.; Weifeng, Z.; Weixiu, Y.; Zhiling, M.; Xiaoyan, Z.; Liguo, C.; Shenghui, L.; Yanfang, Z. Effects of Time and Height of Shading on Yield and Quality of Pineapple. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *512*, 012101. [CrossRef]
20. Reinhardt, D.H.; Uriza, D.; Soler, A.; Sanewski, G.; Rabie, E.C. Limitations for Pineapple Production and Commercialization and International Research towards Solutions. *Acta. Hortic.* **2019**, *1239*, 51–64. [CrossRef]
21. de Araújo, H.S.; Do Carmo, S.A.; Dos Santos, N.C.B.; Freitas, P.G.N.; Purquerio, L.F.V. Effect of Shading Screens on the Production and Quality of 'Smooth Cayenne' Pineapple. *Pesqui. Agropecu. Trop.* **2021**, *51*, e69594. [CrossRef]
22. Santos, I.L.N.; Coelho, E.F.; Barbosa, D.H.S.G.; Lima, L.W.F.; de Pádua, T.R.P.; Junghans, D.T. Application of Fertilizers and Root Enhancers by Two Irrigation Systems on 'BRS Imperial' Pineapple. *Rev. Bras. Frutic.* **2022**, *44*, e-882. [CrossRef]
23. Bonomo, R.; Zucoloto, M.; de Souza, J.M.; Magalhães, A.M.d.P.; Baldotto, P.H.d.S.; Campanharo, A. Production and Quality of "Perola" Pineapple under Fertigation. *Emir. J. Food. Agric.* **2020**, *32*, 109–116. [CrossRef]
24. Umi, H.N.; Tricahya, R.A.; Farid, A.M. Performance Analysis of Drip and Sprinkler Irrigation on Pineapple Cultivation. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *451*, 012034.
25. Yan, C.; An, D.; Liu, Y.; Ma, H.; Dou, M. The Effects of Seasonal Drought on Rainfall Infiltration in Pineapple Plantation under Mulched Drip Irrigation. *J. Irrig. Drain.* **2021**, *40*, 25–32.
26. De Almeida, U.O.; Cades, M.; Andrade Neto, R.D.C.; De Oliveira, L.C. Quality of Pineapple (Cv. Brs Rbo) in different Planting Times with Supplemental Irrigation and Rainfed. *Irriga* **2022**, *27*, 193–207.
27. Harris, I.; Osborn, T.J.; Jones, P.; Lister, D. Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. *Sci. Data* **2020**, *7*, 109. [CrossRef]
28. Uriza-Ávila, D.E.; Torres-Ávila, A.; Aguilar-Ávila, J.; Santoyo-Cortes, V.H.; Zetina-Lezama, R.; Rebolledo-Martínez, A. *La Piña Mexicana Frente al Reto de La Innovación. Avances y Retos en la Gestión de la Innovación*; Colección Trópica Húmeda: Estado de México, México, 2018; p. 484.
29. Dos Santos, M.P.; Maia, V.M.; Oliveira, F.S.; Pegoraro, R.F.; Dos Santos, S.R.; Aspiazú, I. Estimation of Total Leaf Area and d Leaf Area of Pineapple from Biometric Characteristics. *Rev. Bras. Frutic.* **2018**, *40*, e-556. [CrossRef]
30. Gómez-Herrera, M.D.; Alayón-Luaces, P.; Avanza, M.V. Organic Compounds Determined at Different Levels of Ripening of the Pineapple (*Ananas comosus* L. Merr.) Cv Cayenne in Two Cultivation Systems under Subtropical Conditions. *Int. J. Fruit Sci.* **2020**, *20*, 371–384. [CrossRef]
31. Cadahía-López, C. *La Savia como Índice de Fertilización. Cultivos Agroenergéticos, Hortícolas, Frutales y Ornamentales*; Ediciones Mundi-Prensa: Madrid, Spain, 2008; p. 256.
32. AOAC. *Official Methods of Analysis of the AOAC, Methods 932.06, 925.09, 985.29, 923.03*; Association of Official Analytical Chemists: Arlington, VA, USA, 1990.
33. Aragón, C.; Carvalho, L.; González, J.; Escalona, M.; Amancio, S. The Physiology of Ex Vitro Pineapple (*Ananas comosus* L. Merr. Var MD-2) as CAM or C3 Is Regulated by the Environmental Conditions. *Plant Cell. Rep.* **2012**, *31*, 757–769. [CrossRef]
34. Rainha, N.; Medeiros, V.P.; Ferreira, C.; Raposo, A.; Leite, J.P.; Cruz, C.; Pacheco, C.A.; Ponte, D.; Silva, A.B. Leaf Malate and Succinate Accumulation Are out of Phase throughout the Development of the CAM Plant *Ananas comosus*. *Plant Physiol. Biochem.* **2016**, *100*, 47–51. [CrossRef]

35. Ming, R.; VanBuren, R.; Wai, C.M.; Tang, H.; Schatz, M.C.; Bowers, J.E.; Lyons, E.; Wang, M.-L.; Chen, J.; Biggers, E.; et al. The Pineapple Genome and the Evolution of CAM Photosynthesis. *Nat. Genet.* **2015**, *47*, 1435–1442. [CrossRef]
36. do Couto, T.R.; da Silva, J.R.; de Oliveira Moraes, C.R.; Ribeiro, M.S.; Netto, A.T.; Carvalho, V.S.; Campostrini, E. Photosynthetic Metabolism and Growth of Pineapple (*Ananas comosus* L. Merr.) Cultivated Ex Vitro. *Theor. Exp. Plant Physiol.* **2016**, *28*, 333–339. [CrossRef]
37. Qiu, S.; Xia, K.; Yang, Y.; Wu, Q.; Zhao, Z. Mechanisms Underlying the C3–CAM Photosynthetic Shift in Facultative CAM Plants. *Horticulturae* **2023**, *9*, 398. [CrossRef]
38. Joshi, R.; Singh, J.; Vig, A.P. Vermicompost as an Effective Organic Fertilizer and Biocontrol Agent: Effect on Growth, Yield and Quality of Plants. *Rev. Environ. Sci. Biotechnol.* **2015**, *14*, 137–159. [CrossRef]
39. Li, H.; Mei, X.; Wang, J.; Huang, F.; Hao, W.; Li, B. Drip Fertigation Significantly Increased Crop Yield, Water Productivity and Nitrogen Use Efficiency with Respect to Traditional Irrigation and Fertilization Practices: A Meta-Analysis in China. *Agric. Water Manag.* **2021**, *244*, 106534. [CrossRef]
40. Singh, T.B.; Ali, A.; Prasad, M.; Yadav, A.; Shrivastav, P.; Goyal, D.; Dantu, P.K. Role of Organic Fertilizers in Improving Soil Fertility. In *Contaminants in Agriculture: Sources, Impacts and Management*; Naeem, M., Ansari, A.A., Gill, S.S., Eds.; Springer Nature: Cham, Switzerland, 2020; pp. 61–77.
41. Cheng, Y.; Luo, M.; Zhang, T.; Yan, S.; Wang, C.; Dong, Q.; Feng, H.; Zhang, T.; Kisekka, I. Organic Substitution Improves Soil Structure and Water and Nitrogen Status to Promote Sunflower (*Helianthus Annuus* L.) Growth in an Arid Saline Area. *Agric. Water Manag.* **2023**, *283*, 108320. [CrossRef]
42. Zhai, L.; Wang, Z.; Zhai, Y.; Zhang, L.; Zheng, M.; Yao, H.; Lv, L.; Shen, H.; Zhang, J.; Yao, Y.; et al. Partial Substitution of Chemical Fertilizer by Organic Fertilizer Benefits Grain Yield, Water Use Efficiency, and Economic Return of Summer Maize. *Soil Tillage Res.* **2022**, *217*, 105287. [CrossRef]
43. Li, X.; Li, B.; Chen, L.; Liang, J.; Huang, R.; Tang, X.; Zhang, X.; Wang, C. Partial Substitution of Chemical Fertilizer with Organic Fertilizer over Seven Years Increases Yields and Restores Soil Bacterial Community Diversity in Wheat–Rice Rotation. *Eur. J. Agron.* **2022**, *133*, 126445. [CrossRef]
44. Wan, D.; Ma, M.; Peng, N.; Luo, X.; Chen, W.; Cai, P.; Wu, L.; Pan, H.; Chen, J.; Yu, G.; et al. Effects of Long-Term Fertilization on Calcium-Associated Soil Organic Carbon: Implications for C Sequestration in Agricultural Soils. *Sci. Total Environ.* **2021**, *772*, 145037. [CrossRef] [PubMed]
45. Rios, E.S.C.; Mendonça, R.M.N.; Cardoso, E.D.A.; Da Costa, J.P.; De Melo Silva, S. Quality of "Imperial" Pineapple Infructescence in Function of Nitrogen and Potassium Fertilization. *Rev. Bras. Cienc. Agrar.* **2018**, *13*, 1–8. [CrossRef]
46. Cunha, J.M.; Freitas, M.S.M.; de Carvalho, A.J.C.; Caetano, L.C.S.; Vieira, M.E.; Peçanha, D.A.; Lima, T.C.; de Jesus, A.C.; Pinto, L.P. Pineapple Yield and Fruit Quality in Response to Potassium Fertilization. *J. Plant Nutr.* **2021**, *44*, 865–874. [CrossRef]
47. FAO CODEX ALIMENTARIUS. Available online: https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS+182-1993%252FCXS_182e.pdf (accessed on 25 January 2024).
48. Shamsudin, R.; Daud, W.R.W.; Takriff, M.S.; Hassan, O. Physicochemical Properties of the Josapine Variety of Pineapple Fruit. *Int. J. Food Eng.* **2007**, 3. [CrossRef]
49. Hajar, N.; Zainal, S.; Nadzirah, K.Z.; Roha, A.M.S.; Atikah, O.; Elida, T.Z.M.T. Physicochemical Properties Analysis of Three Indexes Pineapple (*Ananas comosus*) Peel Extract Variety N36. *APCBEE Procedia* **2012**, *4*, 115–121. [CrossRef]
50. Saradhuldhat, P.; Paull, R.E. Pineapple Organic Acid Metabolism and Accumulation during Fruit Development. *Sci. Hortic.* **2007**, *112*, 297–303. [CrossRef]
51. Gao, Y.; Yao, Y.; Chen, X.; Wu, J.; Wu, Q.; Liu, S.; Guo, A.; Zhang, X. Metabolomic and Transcriptomic Analyses Reveal the Mechanism of Sweet-Acidic Taste Formation during Pineapple Fruit Development. *Front. Plant Sci.* **2022**, *13*, 971506. [CrossRef] [PubMed]