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ARTICLE

Effects of Chlorine-Based Fertilizers on Tomato Growth under Soilless Culture

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ABSTRACT

This study investigated the effects of chlorine-based fertilizers under varying nitrogen solution concentrations in a soilless culture system. The experiment included four nitrogen solution concentration levels, with nitrogen concentrations of 6 mmol/L (C1), 12 mmol/L (C2), 18 mmol/L (C3), and 24 mmol/L (C4). Each nutrient concentration level was further divided into four chloride ion treatments (R1, R2, R3, and R4), where 100%, 60%, 33%, and 0% of the NH_4^+ and K^+ ions were derived from NH_4Cl and KCl, respectively. The length, surface area and volume of root were significantly higher by 25.3%~136.9%, 40.1%~173.1%, 27.9%~178.0%, respectively, in the R4 treatment than in the R1 and R2 treatments at flowering stage. The aboveground biomass and yield in the R4 treatment were significantly higher, by approximately 15.6%~43.5% and 16.6%~28.6%, respectively, than in the R1, R2, and R3 treatments at the picking stage. The C3 and C4 treatments significantly decreased biomass and yield by 31.9% ~50.2% and 20.7%~50.5%, respectively, compared to the C1 and C2 treatments at the picking stage. Besides, the higher nutrient solution increased the incidence of blossom-end rot. In conclusion, high concentrations of chloride ions in nutrient solutions, especially when the Cl^- concentration exceeded 10 mmol/L, have been shown to inhibit tomato growth in soilless culture systems. Therefore, replacing sulfur-based fertilizers by chlorine-based fertilizers is not recommended for tomato production under the studied conditions.

KEYWORDS

Sand culture; chloride ion; nitrogen solution concentration; tomato yield; blossom-end rot

1 Introduction

Potash and ammonium nitrogen fertilizers primarily comprise chloride or sulfate compounds. Compared with sulfur-based fertilizers, chlorine-based fertilizers offer higher solubility, more abundant resources, and lower costs. Plant chloride ions play crucial roles in maintaining cellular osmotic balance, regulating stomatal movements, supporting photosynthesis, and mitigating diseases like wheat leaf rust, spot blight, barley root-knot, and potato brown heart disease [1]. Despite this, chloride-based fertilizers are often discouraged in cash crops, mainly due to the prevalence of chloride-sensitive varieties. However, recent studies suggest that moderate application of chlorine-based fertilizers does not negatively impact crop growth [2,3]. Shi et al. [4] observed no significant yield differences in cabbage, tomato, cauliflower, *Vigna unguiculata*, and spinach when treated with ammonium chloride compared to equal amounts of ammonium sulfate and urea, without compromising quality.

Similarly, Wang et al. [5] noted that chloride concentrations between 100 and 200 mg/kg positively influenced the growth of peanuts, potatoes, soybeans, and strawberries. Wang et al. [6] found that applying 239 kg/hm^2 of KCl significantly increased watermelon yield. Moreover, Bellof et al. [7] demonstrated that moderate chloride ion levels could enhance strawberries' yield and quality. However, some studies indicate that chloride-based fertilizers can hinder average crop growth and development, leading to substantial yield reductions or crop failure [8,9]. Zhang et al. [10] discovered that high chloride concentrations (169–295 mmol/L) impeded watermelon growth, while Lu [11] found similar effects on potatoes. High chloride levels disrupt plant cell ultrastructure and mitochondrial matrix, leading to vacuolization and structural thickening of the inner mitochondrial membrane. Additionally, chloride accumulation causes cytoplasmic reticulation and increased local concentrations, triggering plasmolysis.

While most research on chlorine effects on crops focuses on field cultivars and soil culture [12–14], soilless culture, including hydroponics, rapidly evolves in China. The soilless culture area covered 6250 hectares in 2018, growing at a compound annual rate of 68% from 2014 to 2018 [15], and is projected to expand to 16,560 hectares by 2023 in China [16]. Soilless culture addresses the challenges of limited arable land and soil degradation [17]. Combined with artificial intelligence advancements, it promises more efficient and precise water and fertilizer management, potentially enhancing agricultural production quality and efficiency. Given that substrates in soilless culture are less buffered than soil, water and fertilizer management demands are more stringent. This study investigates the impact of various chloride- and sulfur-based fertilizers on tomato yield and quality under sand culture, providing insights for optimal fertilizer management in substrate culture.

2 Materials and Methods

2.1 Experimental Overview

The study was conducted in a greenhouse in Mucheng Village, Luocheng Street, Shouguang City, Shandong Province, China (36°88′N, 118°73′E) from February to June 2019. We used the tomato variety 'Fen Zuan 88' (Zhihe Shangnong Co., Ltd., Weifang, China). Plants were potted in sand with 37% total porosity. Each pot, pre-lined with gauze at the bottom and perforated at the lower walls for drainage, was filled with 11.5 kg of the substrate. Black plastic pots (28 cm top diameter, 18 cm bottom diameter, 23 cm height) were used.

2.2 Experiment Design

An utterly randomized group design focused on two experimental factors: nitrogen solution concentration and anion composition (SO_4^{2-} and Cl^-). The nutrient solution comprised four levels: C1, C2, C3, and C4, with nitrogen concentrations of 6, 12, 18, and 24 mmol/L, respectively, while concentrations of all other ions increased proportionally. The SO_4^{2-} and Cl^- composition included the following four levels. The experiment consisted of a total of 16 treatments, each of which was replicated four times. A total of 128 pots were sampled at the flowering and picking stages. Concentrations of sulfur and chlorine under each treatment combination are shown in Table 1.

Table 1: Sulfate and chloride ion concentrations in different concentrations of nutrient solution

Nitrogen solution concentration (mmol/L)	Sulfur ion (SO_4^{2-}) and chlorine ion (Cl^-) concentrations (mmol/L)							
	R1		R2		R3		R4	
	SO_4^{2-}	Cl^-	SO_4^{2-}	Cl^-	SO_4^{2-}	Cl^-	SO_4^{2-}	Cl^-
6	0.0	5.0	1.0	3.0	1.7	1.7	2.5	0.0
12	0.0	10.0	2.0	6.0	3.3	3.3	5.0	0.0
18	0.0	15.0	3.0	9.0	5.0	5.0	7.5	0.0
24	0.0	20.0	4.0	12.0	6.7	6.7	10.0	0.0

Pure water was used in the recovery stage during the first week after planting, followed by the commencement of experimental treatments in the second week. Water and fertilization were managed using an automated drip irrigation system. The nutrient solution was applied every 5 days at 1000 mL/pot during the early stage of tomato growth. The frequency was then increased to 1–2 times a day, based on the increases in biomass and evaporation during the later stages of development. At this point, the rate was set at 400 mL/pot.

2.3 Sampling and Analysis

At the flowering stage (80 days after planting) and picking stage (105 days after planting), the root, plant, and fruit samples were collected to measure the root morphological indexes (root length and root surface area), plant biomass, and yield and quality index (including soluble sugars, vitamin C content, and organic acid concentration) of fruits. Root morphological indexes were scanned using a WinRHIZO root analyzer, and soluble sugar was determined using the anthraquinone-sulfuric acid colorimetric method. In contrast, Vitamin C (Vc) and organic acid concentration were determined via 2,6-dichloroindophenol titration and NaOH titration, respectively.

Microsoft Excel 2010, SAS, and Origin 8.5 were used for data processing, analysis, and graphing. Significant differences between treatments were determined based on the Least Significant Distance (LSD) method ($p < 0.05$) for multiple comparisons.

3 Results

3.1 Tomato Biomass, Yield, and Blossom End Rot Incidence

Nitrogen solution concentration and compositions of SO_4^{2-} and Cl^- significantly affected the aboveground biomass of tomatoes, with a notable interaction between these factors (Table 2). During the flowering stage and picking stage, lower concentrations (C1 and C2) were more beneficial, resulting in biomass increases of 13.8% to 50.5% and 5.6% to 125.5% compared to C3 and C4, respectively (Fig. 1). This trend was similarly reflected in yield, with C1 and C2 treatments enhancing yields by 26.1% to 101.7% compared to C3 and C4 treatments (Table 3).

Table 2: Effect of nitrogen solution concentration and sulfur- and chlorine-based fertilizers on aboveground biomass

Variation source	Flowering stage			Picking stage		
	df	*F*	*Sig.*	*df*	*F*	*Sig.*
Nitrogen solution concentration (C)	3	18.84	0.0001	3	141.694	0.0001
Sulfur or/and chlorine composition (R)	3	6.013	0.0015	3	33.117	0.0001
C × R	9	1.515	0.1699	9	5.791	0.0001

Chloride ions inhibited tomato growth and higher chlorine ion concentrations in R1 and R2 treatments resulted in a decrease in aboveground biomass by 4.4% to 21.2% and 3.4% to 31.0%, respectively, compared to R3 and R4 treatments (Fig. 1).

The plant's incidence of blossom-end rot increased with higher nitrogen solution concentrations and a greater proportion of chloride-based fertilizer. A significant increase of 68.0% in blossom-end rot was noted under the C4 treatment compared to the C3 treatment. Conversely, the R4 treatment, which lacked chlorine, showed a substantial reduction in rot incidence by 13.4% to 46.4% compared to R1, R2, and R3 treatments. Additionally, yields were significantly lower, by 17.0% to 28.7%, in chlorine-containing treatments (R1, R2, R3) than in the chlorine-free treatment (R4) (Table 3).

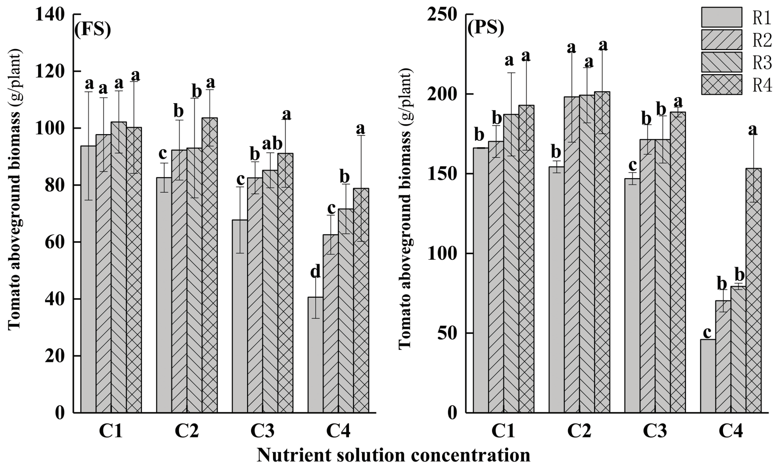

Figure 1: Effect of nitrogen solution concentration and sulfur- and chlorine-based fertilizers on tomato aboveground biomass during flowering (FS) and picking (PS) stages

Table 3: Effect of nitrogen solution concentration and sulfur- and chlorine-based fertilizers on tomato yield, root biomass and blossom end rot incidence during the picking stage

Item	Treatments	R1	R2	R3	R4	Average
Yield (g/plant)	C1	1528(70) Ab	1624(37) Ab	1551(48) Ab	1795(60) Aa	1625 A
	C2	1350(20) Aa	1395(13) Ba	1403(23) Aa	1521(53) Ba	1417 B
	C3	990(29) Bb	1002(9) Cb	1094(22) Bb	1410(8) Ba	1124 C
	C4	587(9) Cc	775(29) Db	853(18) Cb	1006(19) Ca	805 D
	Average	1114 b	1199 b	1225 b	1433(37) a	
Root biomass (g/plant)	C1	22.8(0.8) Ac	26.5(0.3) Ab	28.4(1.1) Aa	29.2(1.3) Aa	26.7(0.9) A
	C2	17.3(2.1) Bd	21.1(1.8) Bc	31.0(1.2) Bb	35.7(3.3) Ba	26.3(2.1) A
	C3	14.9(3.0) Bb	16.3(2.1) Cb	19.8(0.8) Ca	20.7(2.2) Ca	17.9(2.0) B
	C4	7.1(1.6) Cc	12.4(0.6) Db	16.4(2.6) Da	17.5(3.5) Ca	13.3(2.1) C
	Average	15.5 d	19.1 c	23.9 b	25.8 a	
Blossom-end rot incidence (%)	C1	0(0) C	0(0) C	0(0) C	0(0) C	0 C
	C2	0(0) C	0(0) C	0(0) C	0(0) C	0 C
	C3	25(0.2) B	18.7(0.4) B	18.8(0.2) B	18.8(0.7) B	20.3 B
	C4	50(0.3) A	37.5(0.1) A	27.5(0.3) A	21.3(0.2) A	34.1 A
	Average	18.8 a	14.1 b	11.6 c	10.0 c	

Note: Values are means (SD) (n = 3). Values within a row with different lowercase letters and within a column with different uppercase letters are significantly different at $p < 0.05$.

Therefore, low nitrogen solution concentration sulfur-based fertilizers are advisable. Specifically, the R4C1 treatment yielded 1.1 to 3.1 times more than the other treatments (Table 3).

3.2 Tomato Root Growth

Using chloride-based fertilizers inhibited root growth during both the flowering and picking stages. At the flowering stage, root length, surface area, and volume in R1 and R2 treatments were only 66.2%, 61.6%, and 60.1%, respectively, of those in R3 and R4 treatments. Additionally, R4 treatment significantly increased root length, surface area, and volume by 1.8 to 2.2 times compared to R1 (Fig. 2). At the picking stage, root biomass in R1 and R2 treatments was significantly lower, by 20.1% to 39.9%, than in R3 and R4 (Table 3).

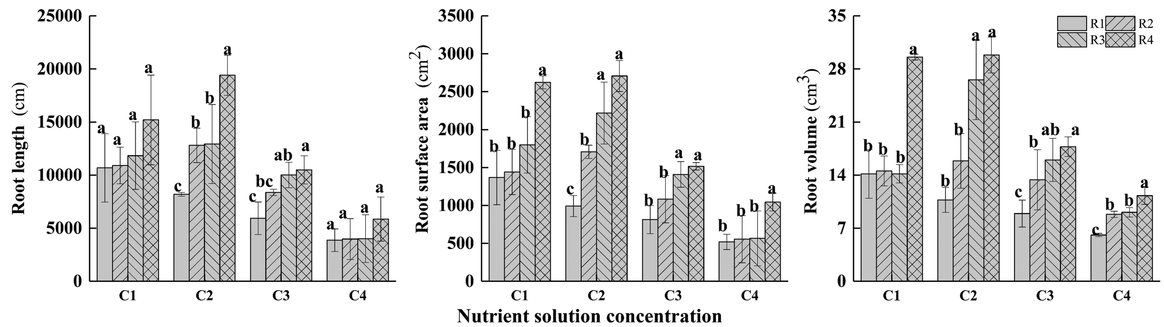

Figure 2: Effect of nitrogen solution concentration (C1: 6 mmol N/L, C2: 12 mmol N/L, C3: 18 mmol N/L, C4: 24 mmol N/L) and sulfur- and chlorine-based fertilizers (R4: all of the NH_4^+ and K^+ derived from $(NH_4)_2SO_4$ and K_2SO_4, R1, R2, and R3: the Cl^- replaced 100%, 75%, 50% SO_4^{2-}) on root length, root surface area and root volume during flowering stage

During the flowering stage, root length, root surface area and root volume have significantly increased by 40.0%~200.7%, 50.0%~184.0% and 29.3%~136.4% under C1 and C2 treatment compared with C3 and C4 treatment, respectively (Fig. 2). During the picking stage, the root biomass increased by 49.2%~100.8% under the C1 treatment and 46.9%~97.7% under the C2 treatment, compared to C3 and C4 treatments (Table 3).

During the flowering stage, low nitrogen solution concentrations combined with high-sulfur treatments (C1R3, C1R4, C2R3, C2R4) were more favorable for root growth, root length and volume were 1.3~5.0- and 1.1~7.3-fold higher under R4C1 and R4C2 treatment compared with all other treatments, respectively (Fig. 2). the high nitrogen solution concentration and high-chloride combinations severely inhibiting root growth during picking stage.

3.3 Tomato Fruit Quality

Increasing nitrogen solution concentration resulted in more significant organic acid and soluble sugar concentration and reduced the sugar-acid ratio. Under the C1 treatment, the organic acid and soluble sugar concentration decreased significantly by 18.0%~47.5% and 15.6%~25.4%, respectively, while the sugar-acid ratio increased considerably by 2.6%~41.6% compared to all other concentrations (Fig. 3). The vitamin C concentration under C4 treatment was significantly reduced by 16.8~24.1 mg/kg compared to all other concentrations (Fig. 3).

The organic acid, soluble sugar, and sugar-acid concentrations increased by an average of 15.3%, 28.8% and 14.5% under R2 and R3 compared to R4 treatment, respectively. Overall, chlorine application (R1, R2, R3) caused a significant reduction in Vitamin C concentration of 5.9–25.5 mg/kg compared to the non-chlorine treatment (R4).

The low-nitrogen solution concentrations and low-chloride treatments had a more beneficial effect on fruit quality. An increase in vitamin C of 2.6%~73.1% was observed under R4C1 treatment compared with all other treatments, while a significant increase in the sugar-acid ratio of 4.0%~130.4% was observed under R3C1 and R3C2 (Fig. 3).

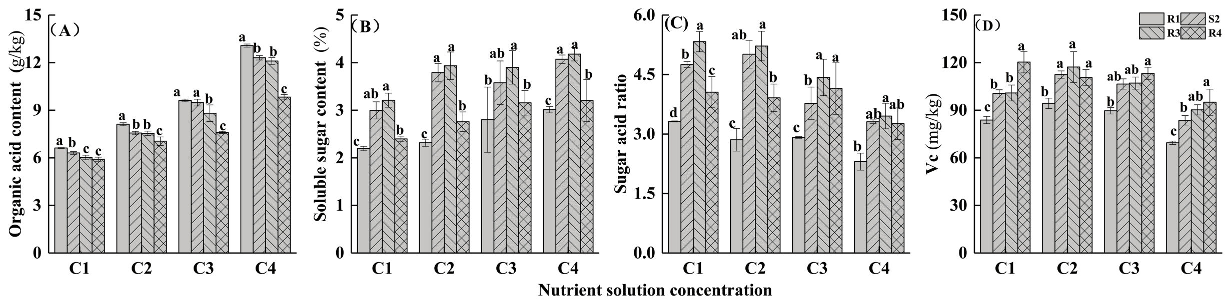

Figure 3: Effect of nitrogen solution concentration (C1: 6 mmol N/L, C2: 12 mmol N/L, C3: 18 mmol N/L, C4: 24 mmol N/L) and sulfur- and chlorine-based fertilizers (R4: all of the $NH4^+$ and K^+ derived from $(NH4)_2SO_4$ and K_2SO_4, R1, R2, and R3: the Cl^- replaced 100%, 75%, 50% SO_4^{2-}) on the organic acid concentration (A), soluble sugar concentration (B), sugar acid ratio (C), and Vc concentration (D)

4 Discussion

The current N recommendation for open soilless greenhouse tomato production amounts to 16 mmol L^{-1} [18]. This study achieved the highest tomato yield with a nitrogen concentration of 6 mmol/L. The difference from the earlier recommendation can be attributed to using a short-term pot experiment. On the one hand, the shorter duration of the pot experiment, along with lower biomass, yield, and nutrient demand of tomatoes compared to field production, contributed to the observed results. On the other hand, the higher frequency of nitrogen solution irrigation during the experiment ensured timely nitrogen supply. In the later stages of tomato growth, the irrigation frequency was as high as 1–2 times per day, which helped maintain a consistent nitrogen supply through frequent nitrogen solution management.

There is a prevalent concern regarding the use of chlorine in agricultural production, particularly in vegetable culture. Most chlorine-based fertilizers are often blindly rejected due to their perceived negative impacts on yield and taste. However, Zhang et al. [10] revealed that exogenous chlorine treatment ranging from 6.25 to 100 mmol/L did not inhibit crop yield but increased seedling biomass and significantly improved seedling uptake and utilization efficiency. Neocleous et al. [19] reported that replacing 1/3 of the standard NO_3^- supply by Cl^- in closed hydroponic tomato crops enhances N use by two-fold and eliminates NO_3^- losses to one-half, with no significant effects on assimilation processes and fruit biomass production. In contrast, in our study, the addition of chloride, particularly at high nitrogen solution concentrations, significantly inhibited the growth of aboveground parts and roots, reduced yield, and increased the incidence of blossom-end rot at the flowering and picking stages. Then, the R1 treatment resulted in a significantly lower yield than R4 by 319.2 g/plant. This is also consistent with the findings of Zhang and Guo et al. [10,15]. Turhan et al. [20] also reported that water containing more than 3.0 mM chlorine will jeopardize yield and quality. High chloride levels may cause osmotic water loss in roots, disrupting normal cell metabolism, leading to physiological drought, and, in severe cases, wilting or plant death. Excessive chloride ions can also disrupt or destroy ionic balance within cells, causing secondary stress, such as nutrient deficiencies from inhibited K^+ and Ca^{2+} uptake [21], explaining the high incidence of blossom-end rot in R1 treatment.

5 Conclusions

The high concentrations of chlorine (≥10 mmol/L) combined with high nitrogen solution concentrations (18 and 24 mmol N/L) inhibited tomato growth, resulting in lower fruit quality and yield and higher blossom-end rot incidence. Therefore, it is advisable to use a combination of lower chlorine concentrations (≤3.0 mmol/L) and nitrogen solutions (6 to 12 mmol N/L) during the flowering and picking stages.

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Author Contributions: The authors confirm contribution to the paper as follows: Experimental design and management: Fei Li; Manuscript preparation: Fei Li, Siping Wang; Review the manuscript, revise and edit this manuscript: Meili Ding; Data collection and formal analysis: Hui Yuan; Project administration: Bin Liang. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author, Bin Liang, upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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