



Influence of Saline Irrigation on Leaf Growth, Nutrient Accumulation, and Soil Properties in Coconut Seedlings

Dang Hoa Tran ^{1*}, Duan Nguyen ¹, Thi Hoang Dong Tran ², Doan Huu Tri Nguyen ³ and Nguyen Quynh Thu Thai ³

¹Hue University, Hue City, Vietnam

²University of Agriculture and Forestry, Hue University, Hue City, Vietnam

³Research Institute for Oil and Oil Plants of Vietnam, Ho Chi Minh City, Vietnam

*Corresponding author: tdanghoa@hueuni.edu.vn

ABSTRACT

Coconut (*Cocos nucifera* L.) is a key tropical perennial crop with notable tolerance to moderate salinity, yet extreme saline conditions can impair growth and productivity. This study investigated the effects of saline irrigation on nutrient accumulation, leaf growth, and soil properties in Dua Ta coconut seedlings under greenhouse conditions. Five salinity levels (0.89, 6.25, 18.25, and 24.5dSm⁻¹) were applied to five-month-old seedlings over 12 months. Leaf growth, biomass, leaflet formation, and nutrient concentrations in roots and leaves were measured, along with changes in soil physicochemical properties. Results indicated that increasing salinity reduced leaf number, length, width, biomass, and leaflet formation, with the most severe effects at 24.5dSm⁻¹. High salinity increased soil EC, TDS, and Na⁺/Cl⁻ concentrations while reducing organic carbon, nitrogen, phosphorus, calcium, and magnesium. Mild salinity ($\leq 6.25\text{dSm}^{-1}$) had minimal effects, moderate salinity (12.0 – 18.25dSm⁻¹) partially inhibited growth, and extreme salinity (24.5dSm⁻¹) severely disrupted physiological functions. The study highlights the interconnected pathway linking saline irrigation, soil nutrient availability, root nutrient uptake, and leaf growth, providing mechanistic insight to guide management strategies for sustaining coconut productivity under salinity stress.

Keywords: Coconut seedling growth, Salt stress, Saline irrigation, Soil nutrient, Root nutrient uptake.

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INTRODUCTION

Coconut (*Cocos nucifera* L.) is a major tropical perennial crop, providing essential food, oil and income in many coastal and island regions (Nampoothiri & Parthasarathy, 2018; Beveridge et al., 2022). By 2020, the global area under coconut cultivation reached 11,575,275 hectares, producing 61,520,382 tons (FAO, 2022). Although its economic returns are moderate compared to other perennial crops, coconut cultivation is stable and ecologically sustainable. It is often recommended as a replacement for low-yielding crops to enhance economic value and prevent soil erosion along rivers and coastlines (George et al., 2018). Recent FAO assessments (2023) highlight that more than 80 million people depend directly on the coconut sector, particularly in climate-vulnerable

Asia-Pacific countries such as the Philippines, Indonesia, India, Sri Lanka and Vietnam. With climate change intensifying coastal flooding, drought cycles, heatwaves, and saline intrusion, coconut is increasingly recognized as a strategic climate-resilient crop (Edna et al., 2023; Jan et al., 2023). Emerging global reviews emphasize that perennial crops with deep root systems—such as coconut—will play a central role in supporting resilient coastal and island agriculture. However, climate-driven changes in soil salinity pose a substantial threat to coconut productivity, particularly in low-lying delta regions. Coconut exhibits high salt tolerance, thriving in soils with electrical conductivity (EC) up to 11.07dSm⁻¹ and under irrigation with saline water up to 10.1dSm⁻¹ (Lima et al., 2017; Medeiros et al., 2018). However, a recent study reported that coconut seedlings irrigated with water having an EC of

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24.5dSm⁻¹ experienced significant growth reductions, including impaired leaf development, indicating a high sensitivity to extreme saline conditions (Thai et al., 2024). Salt-tolerant varieties are therefore suitable for coastal areas affected by salinity due to sea-level rise, making coconut naturally adapted to such environments (Santos et al., 2020; Kumar & Kunhamu, 2022). Nevertheless, prolonged exposure to salinity can significantly reduce overall growth and productivity by inducing ion toxicity, osmotic and oxidative stress, and nutrient imbalances, which directly impact leaf expansion, leaf area, and canopy development (Lima et al., 2017; Silva et al., 2017; Medeiros et al., 2018). Salinity has emerged as one of the most critical production constraints in coconut-dominant coastal landscapes. According to IPCC (2023), sea levels could rise by 0.43–0.84m by 2100, significantly amplifying seawater intrusion into agricultural lands. FAO (2024) reports that more than 20% of irrigated land globally is already salt-affected, with projections indicating further expansion in tropical and subtropical coastal regions. Studies from Sri Lanka, India, Indonesia, and the Philippines show that salinization is accelerating in coconut-growing belts due to groundwater over-extraction, sea-level rise, and tidal flooding (Ghirardelli et al., 2025). These observations reinforce the need to understand coconut responses to saline irrigation under changing climate conditions.

Saline irrigation affects plant growth by disrupting water uptake and nutrient accumulation, as excess sodium (Na⁺) and chloride (Cl⁻) ions compete with essential nutrients such as potassium (K⁺), calcium (Ca²⁺) and magnesium (Mg²⁺) (Grattan & Grieve, 1999; Akter & Oue, 2018; Kumari et al., 2023; Demo et al., 2025). In coconut, nutrient accumulation in leaves and roots is critical not only for photosynthesis and enzyme activity but also for optimal leaf growth and development (Jayasekara et al., 1996; John Sunoj et al., 2015; Lu et al., 2023). Adequate nutrient concentrations in leaves (e.g., N, P, K, Mg, and Ca) support cell division and expansion, chlorophyll synthesis, and photosynthetic efficiency, while sufficient nutrient reserves in roots ensure continuous nutrient supply to developing leaves. Thus, leaf growth is closely linked to both leaf and root nutrient status, and deficiencies or imbalances can directly reduce leaf area, leaf biomass, and overall plant vigor. Salinity also alters soil physical and chemical properties, potentially degrading soil structure, reducing microbial activity, and limiting nutrient availability (Hou et al., 2021; Pan et al., 2024; Wang et al., 2024). These changes can exacerbate nutrient deficiencies, further compromising leaf growth and long-term soil fertility.

Recent physiological studies on perennial palms and coastal woody species reveal that salinity leads to oxidative stress, disruption of antioxidant systems, altered carbon partitioning, and impaired water-use efficiency (Hao et al., 2021; Melino & Notes, 2023). Na⁺ accumulation interferes with K-dependent metabolic pathways, compromising protein synthesis, osmotic adjustment, and stomatal regulation (Kalaivani et al., 2024). Cl⁻ toxicity reduces photosystem II performance and leaf area expansion. Meanwhile, Ca and Mg depletion in roots weakens membrane integrity and reduces nutrient transport, further affecting leaf growth. These insights underscore the

importance of evaluating nutrient allocation in both leaves and roots when assessing saline stress responses in coconut. Emerging research also highlights that saline irrigation leads to soil structural degradation, reduced hydraulic conductivity, suppressed microbial diversity, and shifts in rhizosphere microbial communities (Zhang et al., 2024). These soil-mediated effects can amplify plant nutrient deficiencies, particularly in perennial plantation crops such as coconut. Because coconut has an extensive and long-lived root system, changes in soil physical and chemical properties under salinity may have long-term consequences for plant nutrition and productivity. However, most salinity research to date has focused on annual crops or model plants, leaving substantial gaps in understanding soil–plant interactions in perennial woody crops such as coconut. Although the effects of salinity on plant physiology are well-documented, integrated assessments of nutrient accumulation in coconut leaves and roots, leaf growth responses, and associated soil changes under saline irrigation remain scarce. Most studies on coconut examine physiological tolerance thresholds, chlorophyll fluorescence, or ion accumulation (Medeiros et al., 2018; Thai et al., 2024).

Few studies have simultaneously investigated nutrient dynamics in both leaves and roots together with soil chemical changes resulting from saline irrigation. Furthermore, no previous work has explicitly quantified how nutrient status in both plant organs relates to leaf growth traits and early canopy formation under controlled salinity levels. This represents a critical knowledge gap in understanding coconut adaptation to salinity. The novelty of this study lies in simultaneously assessing (i) nutrient accumulation in leaves and roots, (ii) leaf growth responses, and (iii) soil chemical changes under saline irrigation—an integrated approach not previously reported for coconut. We hypothesize that increasing irrigation salinity will (1) reduce nutrient accumulation in leaves and roots, particularly K, Ca, and Mg; (2) suppress leaf expansion and biomass production through nutrient imbalance; and (3) modify soil chemical properties in ways that intensify nutrient limitations. The objectives are to: (i) quantify nutrient accumulation in leaves and roots under varying salinity levels; (ii) determine the relationships between nutrient status and leaf growth; and (iii) assess changes in soil chemical properties following saline irrigation.

MATERIALS & METHODS

The experiment was conducted from July 2022 to July 2023 in a greenhouse at the Binh Chanh Experimental Farm, Research Institute for Oil and Oil Plants, Ho Chi Minh City, Vietnam (10°49'46.5"N, 106°44'17.6"E Binh Thanh). The treatments consisted of five levels of water salinity, expressed as electrical conductivity (EC): 0.89, 6.25, 12.0, 18.25, and 24.5dSm⁻¹, with 0.89dSm⁻¹ serving as the control. These salinity levels were selected to represent (i) non-saline to moderately saline irrigation water commonly found in coastal agriculture (0.8–6dSm⁻¹) and (ii) moderate to severe salinity stress (12–25dSm⁻¹). This range aligns with recent coconut salt-tolerance experiments that

evaluated seedling thresholds under comparable EC conditions (Hebbar et al, 2021; Thai et al., 2024).

Five-month-old coconut seedlings (*Cocos nucifera* L., variety Dua Ta, a commonly cultivated variety in Vietnam) were used. At planting, seedlings had two leaves, an average height of 51cm, and a stump girth of 6.9cm. Each seedling was transplanted into a plastic pot (35cm diameter × 30cm depth) containing approximately 10kg of loam soil. Before use, the soil was sieved (5mm), homogenized, and air-dried. The soil was not sterilized in order to preserve its natural microbial community, which is recommended for salinity-response experiments (Jiang et al., 2023). Each pot had four drainage holes (1cm diameter) to allow controlled outflow. To prevent uncontrolled leaching of salts during irrigation, pots were placed on plastic saucers; any drainage water was collected and returned to the pot after sediment settling. The soil properties are presented in Table 7.

Weather conditions during the experiment were recorded daily using an ATMOS-41 complex weather station. The maximum, minimum, and average temperatures were 40.6°C, 23.0°C and 27.5°C, respectively, with an average humidity of 86.5%. The experiment followed a randomized complete block design (RCBD) with three replications and six seedlings per replication. Four days after planting, seedlings were randomly assigned to one of the five salinity levels by irrigating them with saline water solutions. These solutions were prepared by dissolving sodium chloride (NaCl) in fresh water (EC = 0.89 dS m⁻¹) from the urban supply system. The pots were maintained in the greenhouse, and irrigation was performed every four days, with each seedling receiving 1 L of water manually in the late afternoon using a graduated bucket. No fertilizer was applied to avoid nutrient-salinity interaction effects that could confound salt-stress responses. Agronomic traits of all six seedlings in each plot were recorded. Quarterly, the number of leaves per seedling and the number of leaflets per green leaf were counted. Leaf and leaflet length and width were also measured. At the end of the experiment, three surviving seedlings from each plot were randomly selected to measure leaf width and calculate leaf area. All leaves from each selected seedling were bagged separately and oven-dried at 105°C to determine dry matter.

At harvest, leaf and root samples were collected for nutrient analysis (N, P, K, Ca, Mg, Na, and Cl). Entire root systems were washed to remove soil, debris, and damaged roots. For leaf sampling, 10 fourth leaves (counting from the youngest unopened leaf) were collected per plant.

From each leaf, only green tissue was used, with veins removed. Nutrient analyses followed standard wet-chemistry protocols: total N by the Kjeldahl method (Bremner, 1996); P by the molybdenum blue colorimetric method; and K, Ca, Mg, and Na by atomic absorption spectrophotometry according to AOAC (2019). Chloride concentration was determined by silver nitrate titration according to ISO 9297:1989. These procedures have been widely adopted in recent perennial-crop salinity studies (Kumar et al., 2023). Soil samples were also collected before and after the experiment using a soil auger, from the surface to the bottom of the pot. For each treatment, samples were taken from three pots, with about 500g of soil collected per pot.

Data were analyzed using Statistix 10.0 (Analytical Software, Tallahassee, FL, USA). One-way ANOVA was used to compare differences in agronomic traits and biomass among treatments. In all analyses, differences were considered significant at P<0.05.

RESULTS

Salinity Effects on Leaf Growth

Saline irrigation significantly affected both total leaf number and the rate of new leaf emergence in Dua Ta coconut seedlings throughout the experimental period (Table 1). At 3 months after treatment, leaf number decreased progressively with increasing salinity, from 4.4 leaves at 0.89dSm⁻¹ to 2.9 leaves at 24.5dSm⁻¹ (P<0.05). Although seedlings exposed to 6.25dSm⁻¹ maintained a leaf number statistically similar to the control, higher salinity levels (≥12.0dSm⁻¹) caused significant reductions, indicating early sensitivity of leaf initiation to salt stress. This pattern intensified over time. By 12 months, seedlings irrigated with 24.5dSm⁻¹ produced only 4.4 leaves compared with 7.8 leaves in the control, representing a 43.5% reduction. Similarly, the number of newly emerged leaves declined steadily with increasing salinity and exposure duration, reaching zero at 24.5dSm⁻¹ after 12 months.

Leaf length and width were strongly and consistently reduced by increasing salinity (Table 2). At 3 months, leaf length declined from 34.9cm at 0.89dSm⁻¹ to 21.0cm at 24.5dSm⁻¹ (P<0.05), while leaf width decreased more sharply, from 17.9 to 9.9cm (P<0.05). From 6 months onward, salinity-induced inhibition intensified. At 12 months, leaf length under 24.5dSm⁻¹ (36.4cm) was approximately 1.7-fold shorter than in the control (60.2cm). Leaf width could not be recorded for the control at 12

Table 1: Number of leaves per coconut seedling after one year of irrigation with five levels of water salinity

Salinity level (dS m ⁻¹)	Months after irrigation with saline water							
	3		6		9		12	
	No. of leaf	No. of new emerged leaf	No. of leaf	No. of new emerged leaf	No. of leaf	No. of new emerged leaf	No. of leaf	No. of new emerged leaf
0.89	4.4a	0.6a	5.9a	0.5a	7.0a	0.3a	7.8a	0.3a
6.25	4.0a	0.5a	5.3b	0.4ab	6.1b	0.3ab	6.8b	0.2ab
12.0	3.7b	0.5ab	4.6c	0.3bc	5.4c	0.2b	5.8c	0.1bc
18.25	3.3c	0.4b	4.2d	0.3c	4.8d	0.2b	5.2d	0.1bc
24.5	2.9d	0.2c	3.5e	0.2c	4.1e	0.2b	4.4e	0.0c
F	79.87	22.00	22.67	22.67	8.50	8.50	19.33	19.33
P	<0.0001	0.0002	<0.0001	0.0002	<0.0001	0.0056	<0.0001	0.0004

Values in a column followed by same letters are not significantly different by one-way ANOVA, P<0.05.

Table 2: Leaf size parameters of coconut seedlings after one year of irrigation under five salinity levels

Salinity level (dS m ⁻¹)	Months after irrigation with saline water							
	3		6		9		12	
	Length (cm)	Width (cm)	Length (cm)	Width (cm)	Length (cm)	Width (cm)	Length (cm)	Width (cm)
0.89	34.9a	17.9a	47.9a	22.9a	54.9a	24.3a	60.2a	-
6.25	33.6a	15.4b	45.7a	20.5b	49.1b	22.5b	51.6b	24.0a
12.0	29.8ab	11.5c	38.6b	14.5c	43.0c	17.0c	45.5bc	19.3b
18.25	24.0bc	11.3c	32.6c	12.6d	38.2d	13.9d	41.2cd	14.8c
24.5	21.0c	9.9c	29.9c	10.9d	33.9e	11.7e	36.4d	12.0d
F	20.99	109.79	104.11	217.07	101.11	309.79	36.82	481.98
P	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Values in a column followed by same letters are not significantly different by one-way ANOVA, $P < 0.05$; At 12 months after treatment, leaf width data were not recorded, as leaflets had unfolded.

Table 3: Leaflet traits of coconut seedlings after one year of irrigation with five salinity levels

Salinity level (dS m ⁻¹)	Months after irrigation with saline water					
	6			12		
	No. of leaflet	Length (cm)	Width (cm)	No. of leaflet	Length (cm)	Width (cm)
0.89	15.7a	57.5a	1.8a	18.3a	62.3a	2.1a
6.25	0.0b	0.0b	0.0b	16.7b	58.2a	2.2a
12.0	0.0b	0.0b	0.0b	0.0c	0.0b	0.0b
18.25	0.0b	0.0b	0.0b	0.0c	0.0b	0.0b
24.5	0.0b	0.0b	0.0b	0.0c	0.0b	0.0b
F	2820.1	589.22	972.00	1612.7	289.91	715.67
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Values in a column followed by same letters are not significantly different by one-way ANOVA, $P < 0.05$.

months due to leaflet unfolding; however, among saline treatments, width declined markedly from 24.0cm at 6.25dSm⁻¹ to 12.0cm at 24.5dSm⁻¹. Leaflet formation was the most sensitive morphological trait affected by salinity (Table 3). At 6 months, leaflets were observed exclusively in the control treatment (15.7 leaflets per leaf), whereas all saline treatments showed complete suppression. By 12 months, leaflet formation occurred only at 0.89 and 6.25dSm⁻¹, with 18.3 and 16.7 leaflets, respectively; no leaflet development was observed at salinity levels ≥ 12.0 dSm⁻¹.

Salinity also caused a marked decline in leaf biomass and leaf area (Table 4). Fresh leaf weight decreased from 206.0 g per seedling at 0.89dSm⁻¹ to 72.4 g at 24.5dSm⁻¹, while dry weight declined from 60.8 to 22.6 g ($P < 0.05$). Leaf area exhibited the strongest response, decreasing more than threefold from 8.185cm² to 2.492cm² per seedling.

Table 4: Green leaf biomass and leaf area of coconut seedlings after one year of irrigation with five salinity levels

Salinity level (dS m ⁻¹)	Fresh leaf weight (g/ seedling)	Dry leaf weight (g/ seedling)	Leaf area (cm ² /seedling)
0.89	206.0a	60.8a	8185.41a
6.25	157.0b	46.4b	6093.95b
12.0	113.6c	33.7c	4304.58c
18.25	85.3d	27.3d	3088.68d
24.5	72.4d	22.6d	2491.88e
F	344.21	228.82	553.06
P	<0.0001	<0.0001	<0.0001

Soil Chemical Changes and Nutrient Availability under Saline Irrigation

Saline irrigation substantially altered key soil chemical properties (Table 5). Soil electrical conductivity (EC) increased from 0.21dSm⁻¹ in the control to 4.79dSm⁻¹ at the highest salinity level (24.5dSm⁻¹). Total dissolved solids (TDS) increased nearly 20-fold. Soil organic carbon declined from 1.47% to 1.04%. Total and available nitrogen decreased substantially, and similar declines were observed for P and K. Exchangeable Ca²⁺ and Mg²⁺

declined sharply with increasing salinity. In contrast, Na⁺ and Cl⁻ accumulated dramatically, reaching 538.5 and 835.0mg/100g soil, respectively, at 24.5dSm⁻¹.

Table 5: Effects of saline irrigation on soil properties

Parameter	Unit	Before experiment	Salinity level (dS m ⁻¹)				
			0.89	6.25	12.00	18.25	24.50
pH _{H2O}	-	5.5	5.4	5.5	5.5	5.6	5.6
TDS	ppm	153.1	117.2	883.0	994.0	1448.0	2290.0
EC	dS m ⁻¹	0.29	0.21	1.87	1.91	2.32	4.79
CEC	meq100g ⁻¹	14.2	13.6	13.8	13.9	14.1	14.2
OC	%	1.47	1.47	1.45	1.33	1.21	1.04
Total N	%	0.12	0.09	0.08	0.06	0.05	0.04
Available N	mg100g ⁻¹	2.9	0.9	0.9	0.8	0.7	0.7
Total P ₂ O ₅	%	0.16	0.13	0.12	0.12	0.11	0.09
Available P ₂ O ₅	mg100g ⁻¹	42.2	20.4	20.6	21.1	21.5	21.6
Total K ₂ O	%	0.23	0.17	0.16	0.14	0.13	0.13
Available K ₂ O	mg100g ⁻¹	35.6	35.8	35.1	33.6	27.9	27.3
Ca ²⁺	meq100g ⁻¹	7.87	4.75	2.57	1.58	1.49	0.89
Mg ²⁺	meq100g ⁻¹	7.70	5.35	2.38	1.29	0.99	0.59
Na ⁺	mg100g ⁻¹	59.4	30.5	280.4	347.0	426.3	538.5
Cl ⁻	mg100g ⁻¹	13.9	25.0	414.0	425.0	562.0	835.0

Nutrient Imbalance in Roots and Leaves

Salinity reduced concentrations of essential nutrients (N, P, K, Ca, Mg) while increasing Na⁺ and Cl⁻ in roots and leaves (Table 6 & 7). At 24.5dSm⁻¹, leaf Na and Cl contents increased by 166% and 175% relative to the control. Nitrogen, phosphorus, potassium, calcium and magnesium all declined with increasing salinity. In contrast, Na⁺ and Cl⁻ accumulated to high levels, especially in leaves.

Table 6: Effects of saline irrigation on nutrient content (%) in coconut seedling leaves

Parameter	Salinity level (dS m ⁻¹)				
	0.89	6.25	12.0	18.25	24.5
N	1.42	1.31	1.29	1.27	1.19
P ₂ O ₅	0.37	0.36	0.31	0.30	0.29
K ₂ O	2.45	2.44	2.44	2.41	2.39
Ca	0.18	0.16	0.15	0.14	0.12
Mg	1.02	1.01	1.01	1.00	0.99
Na	0.74	1.01	1.07	1.18	1.23
Cl	0.98	1.40	1.47	1.57	1.71

Table 7: Effects of saline irrigation on nutrient content (%) in coconut seedling roots

Parameter	Salinity level (dS m ⁻¹)				
	0.89	6.25	12.00	18.25	24.50
N	0.74	0.72	0.67	0.60	0.58
P ₂ O ₅	0.34	0.30	0.27	0.27	0.28
K ₂ O	1.32	1.05	1.01	0.88	0.90
Ca	0.17	0.15	0.14	0.14	0.13
Mg	0.55	0.44	0.42	0.36	0.36
Na	0.91	2.15	2.35	2.53	2.66
Cl	1.05	3.86	4.46	4.91	5.03

DISCUSSION

Salinity imposes a complex set of constraints on coconut seedlings, acting simultaneously through osmotic stress, ion toxicity, and nutrient imbalance, ultimately suppressing organogenesis and reducing canopy development. The progressive decline in leaf emergence and leaf expansion observed across increasing salinity levels reflects typical plant responses in the early osmotic phase of salt stress. Elevated external osmotic pressure lowers root water potential, restricting water uptake and decreasing turgor required for both meristematic cell division and cell enlargement (Munns, 2002; Munns & Tester, 2008). As cytokinin synthesis in roots is reduced and its transport to shoots becomes impaired under saline conditions, mitotic activity at the shoot apical meristem declines (Bernstein, 2019; Mandal et al., 2022; Yang & Lee, 2023). These coupled physiological limitations explain the consistent reductions in leaf initiation and leaf expansion. As salinity increases, plants enter the ionic phase of stress, where Na⁺ and Cl⁻ accumulation triggers more severe metabolic dysfunction. These ions gradually build up in meristematic tissues and developing leaves, disrupting cell division, vesicle trafficking and hormonal signaling pathways such as auxin–cytokinin balance (Munns, 2005; Zörb et al., 2019). A critical indicator of ion toxicity is the decline in the K⁺/Na⁺ ratio, as excessive Na⁺ competitively inhibits K⁺ uptake at root plasma membrane transporters (Shabala & Cuin, 2008; Assaha et al., 2017). Potassium is essential for maintaining osmotic balance, turgor-driven expansion, stomatal function, and enzyme activation. Consequently, reduced K⁺ availability translates into restricted lateral expansion of leaf lamina—manifesting as narrower leaves—which is widely recognized in palms as a protective morphological adjustment aimed at reducing transpirational surface area (Silva et al., 2017). However, the intensified narrowing in this study suggests a more severe K⁺/Na⁺ disruption and highlights varietal differences in tolerance, as some salt-tolerant hybrids have shown better leaf development under similar or higher salinity levels (Silva et al., 2017).

Leaflet initiation, a developmentally advanced process requiring sustained carbon supply, balanced hormonal signaling and coordinated vascular differentiation, proved the most sensitive trait. Its complete suppression at salinity $\geq 12\text{dSm}^{-1}$ indicates that osmotic and ionic stresses exceeded the developmental resilience threshold of the Ta cultivar. Reduced leaf N and K—direct consequences of both soil nutrient displacement and impaired uptake—limit chlorophyll synthesis, protein formation, and

photosynthetic efficiency, resulting in insufficient assimilates to support leaflet morphogenesis. Elevated Na⁺ and Cl⁻ further impair nitrate assimilation and destabilize membranes (Tester & Davenport, 2003; Acosta-Motos et al., 2017; Zelm et al., 2020), undermining the cellular processes underlying leaflet differentiation. Unlike some coconut genotypes that maintain reduced but persistent leaflet formation under moderate salinity (Melino & Notes, 2023), the complete inhibition observed here indicates a high degree of sensitivity. Soil chemical properties also shifted dramatically under saline irrigation, amplifying stress transmitted to roots and shoots. Soil EC and TDS rose sharply, transforming the rhizosphere into an ion-rich environment with reduced hydraulic conductivity and increased osmotic pressure, which severely restricts water movement toward roots (Rengasamy, 2010; Qadir et al., 2014). Salinity-induced suppression of soil microbial activity—especially nitrifiers and phosphorus-mineralizing microbes—further reduced total and available nitrogen and phosphorus (Zhang et al., 2019; Li et al., 2024). This decline is critical because nitrogen drives chlorophyll synthesis and canopy expansion, whereas phosphorus supports ATP formation and cell division (Munns & Tester, 2008; Zörb et al., 2019). Potassium availability also declined sharply as Na⁺ displaced K⁺ from both soil exchange sites and root transporters, lowering the K⁺/Na⁺ ratio in the rhizosphere and inside plant tissues (Acosta-Motos et al., 2017). This cation displacement mechanism extended to Ca²⁺ and Mg²⁺, whose losses destabilized soil aggregates, increased clay dispersion, and impaired root-zone aeration (Qadir & Schubert, 2002; Rengasamy, 2010). These soil-level processes intensified physiological stress by limiting essential nutrients while accelerating Na⁺ and Cl⁻ influx into roots.

The nutrient profile of roots and leaves mirrored soil changes, with steep declines in N, P, K, Ca, and Mg under increasing salinity. Nitrogen deficiency reduces protein synthesis and chlorophyll content, slowing photosynthesis and leaf initiation (Khan et al., 2015; Hebbar et al., 2021). Phosphorus deficiency limits ATP availability for cell division, explaining the strong inhibition of leaflet morphogenesis (Xie et al., 2022). Calcium depletion compromises membrane stability and increases Na⁺ permeability, amplifying ionic toxicity (White & Broadley, 2003). Magnesium deficiency exacerbates declines in photosynthetic activity because Mg is central to chlorophyll structure and carbon fixation (Marschner, 2012). Meanwhile, excessive Na⁺ and Cl⁻ accumulation triggers oxidative stress, damaging lipids and photosynthetic membranes through ROS overproduction (Hasanuzzaman et al., 2020). The alignment of these findings with the two-phase salinity model (Munns, 2005) confirms that both osmotic and ionic factors contributed significantly to growth inhibition.

The reduction in leaf biomass and leaf area reflects a shift in carbon allocation under salinity. Elevated Na⁺ requires energy-demanding exclusion and compartmentalization processes, increasing maintenance respiration and reducing carbon investment in structural growth (Munns & Gilliam, 2015). Coconut seedlings likely

compensated by producing thicker but smaller leaves—an adaptive response reported in coastal coconut populations (Hebbar et al., 2021). While such adjustments may limit transpiration and ion transport to shoots, they significantly reduce light interception and long-term carbon gain. Therefore, the declining leaf area, suppressed leaf initiation, and inhibited leaflet formation collectively represent a profound reduction in photosynthetic potential.

Overall, the integrated evidence indicates that salinity affects coconut seedlings through tightly interlinked pathways: osmotic inhibition of water uptake, ionic disruption of nutrient homeostasis, soil-mediated nutrient displacement, and metabolic constraints driven by high Na^+ and Cl^- loads. These mechanisms interact synergistically to limit canopy development and leaf morphogenesis, particularly in sensitive cultivars such as Dua Ta coconut. Maintaining nutrient balance—especially the K^+/Na^+ ratio and Ca^{2+} availability—appears crucial for enhancing tolerance during early seedling establishment. The study's findings underscore the need for cultivar-specific salinity thresholds and targeted nutrient management to mitigate long-term productivity losses in saline environments.

Conclusion

Saline irrigation significantly affected leaf development, nutrient accumulation, and soil properties in Dua Ta coconut seedlings. Moderate salinity (6.25 dS m^{-1}) caused only minor reductions in growth, whereas salinity levels $\geq 12.0 \text{ dS m}^{-1}$ led to substantial decreases in leaf number, size, biomass, and leaflet formation, accompanied by nutrient imbalances and soil degradation. High salinity induced severe ion toxicity, characterized by elevated Na^+ and Cl^- and reduced N, P, K, Ca, and Mg in both roots and leaves, while declines in soil organic carbon, total nitrogen, and exchangeable Ca^{2+} and Mg^{2+} further constrained nutrient uptake. Overall, growth inhibition resulted from the combined effects of osmotic stress, ion toxicity, and nutrient depletion, indicating that although coconut shows moderate tolerance, high salinity markedly impairs physiological functioning and seedling vigor. These findings highlight the need for targeted salinity management in coconut production systems, particularly in coastal landscapes prone to long-term salt accumulation. Maintaining irrigation salinity below agronomic thresholds, enhancing soil organic matter, and applying Ca- and Mg-based amendments may help mitigate nutrient displacement and maintain growth under moderate salinity. The integrated soil–root–leaf mechanisms identified here provide a useful basis for developing evidence-based irrigation guidelines and refining field management strategies in salt-affected coconut-growing regions.

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