

Article

Optimizing *Citrus aurantifolia* (Christm. Swingle) Production Through Integrated Irrigation and Growth Regulation Strategies

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Abstract

Optimizing irrigation and the targeted use of plant growth regulators are key strategies to improve productivity in *citrus* systems under water-limited conditions. This study evaluated the effects of three irrigation levels (4.44, 5.18, and 7.77 mm day^{−1}) combined with variable doses of naphthaleneacetic acid (NAA) and gibberellic acid (GA₃) on physiological and productive responses in *Citrus aurantiifolia*. The treatment with 7.77 mm irrigation and moderate doses of NAA (100 mg L^{−1}) and GA₃ (80 mg L^{−1}) increased yield by 38% (6.2 kg/plant), and it enhanced photosystem II photochemical efficiency ($F_v/F_m = 0.82$), chlorophyll index (SPAD = 62), and fruit weight by 15%. In contrast, high hormone doses under water deficit reduced leaf water potential and impaired physiological performance, leading to lower productivity. These findings support the combined use of regulated deficit irrigation and hormonal biostimulation as a sustainable strategy to enhance key lime yield and resource efficiency in semi-arid environments.

Keywords: *Citrus aurantifolia*; irrigation rates; growth regulators; productivity



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1. Introduction

The subtle lemon (*Citrus aurantifolia* (Christm.) Swingle) is a crop of economic and social importance, especially in tropical and subtropical regions. According to the World Citrus Organization [1], global lemon production reached 6,467,616 tons in 2020, led by the European Union, with 1,871,011 tons (28% of the total). In contrast, Ecuador cultivated 6212 hectares, with a production of just 27,914 tons, a low figure compared to other South American countries [2,3].

One of the main constraints to improving lemon productivity in Ecuador is the limited irrigation infrastructure. Only 35.8% of perennial crops have access to irrigation, with the remainder dependent on rainfall patterns [4]. The subtle lemon requires between 1000 and 2000 mm of water per year for optimal development [5]. However, in the province of

Manabí, annual rainfall does not exceed 1000 mm, with 83% of the rainfall concentrated between January and April [6]. This marked water seasonality, coupled with the absence of irrigation systems (more than 65% of producing areas lack them) and the worsening of climate change, severely limits crop yield [4,7].

Water deficit directly affects critical physiological variables, such as net photosynthesis (A), stomatal conductance (g_s), and transpiration (E), negatively impacting crop growth and development [8,9]. Although *citrus* fruits exhibit efficient stomatal regulation as an adaptive response in semi-arid conditions [10], water scarcity during the early stages of fruit development compromises their size and final weight [11]. In this situation, using plant growth regulators (PGRs) like auxins and gibberellins has become important because they can help control processes related to flowering, fruit formation, and fruit quality. In *citrus*, their application has proven effective in improving yield, although there are still gaps regarding their combined effects with different water management strategies [12,13]. Auxins promote cell elongation, fruit development, and delayed ripening [14,15], while gibberellins, particularly gibberellic acid (GA_3), stimulate cell growth and photosynthate accumulation, with dosage and timing being decisive factors [16,17].

In this context, water deficiency in *citrus* not only limits vegetative growth but also impairs fruit quality, resulting in significant economic losses [18,19]. In Ecuador, particularly in the province of Manabí which accounts for the highest production of *Citrus aurantifolia* the lowest harvest period occurs from July to November, coinciding with price increases that reached USD 35 per 35 kg bag in 2018 [3,20].

Strategies that protect the crop against climatic and water limits are essential, given the region's commercial and nutritional worth of lemons and the significance of their supply chain for the local economy. In this way, handling the physiological and hormonal issues of lemon trees through the use of RCV in combination with effective irrigation strategies offers a chance to maximize fruit quality and output in water-stressed environments.

Considering the commercial and nutritional value of lemon in the region, as well as the importance of its production chain for the local economy, it is imperative to implement strategies that strengthen the crop in the face of climatic and water constraints. In this sense, the combination of efficient irrigation techniques and the application of RCV represents an opportunity to address the physiological and hormonal challenges of lemon trees, optimizing fruit yield and quality under water stress conditions.

2. Materials and Methods

2.1. Location of the Study

This study was conducted at the “La Herradura” farm, located along the road to La Unión, in the Ayacucho parish of Santa Ana Canton, Manabí Province, Ecuador. Geographically, the site is situated at a latitude of $1^{\circ}15'75''$ S and a longitude of $80^{\circ}28'23''$ W, at an elevation of 64 m a.s.l. (meters above sea level). The area has an average annual temperature of 26 °C.

2.2. Conditions of the Experiment

The experiment was carried out under tropical dry forest conditions. To characterize the climatic behavior during the study period, a precipitation analysis was carried out based on historical data (2020–2023) from a nearby agrometeorological station. The annual rainfall distribution is shown in Figure 1. During the experimental period (2023), the accumulated precipitation reached 1003.8 mm, with the highest values recorded between the months of February and July, with March (261.1 mm) and July (99.2 mm) standing out. This rainfall pattern coincided with the stages of the crop's greatest physiological activity,

which supports the need to implement complementary irrigation strategies to optimize the production of subtle lemons in semi-arid conditions.

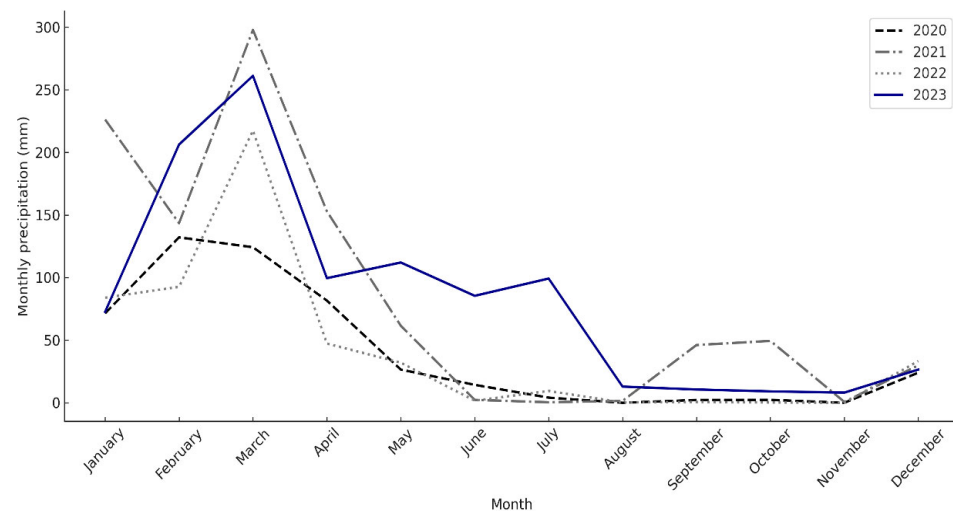


Figure 1. Characterization of climatic behavior during the study period, with precipitation analysis based on historical data (2020–2023) from a nearby agrometeorological station.

2.3. Site Characterization

Soil Characteristics (Soil Analysis)

A composite soil sample was collected in a zigzag pattern, at a depth of 50 cm, and analyzed at the Soil, Plant Tissue, and Water Laboratory of INIAP's Tropical Experimental Station "Pichilingue". The soil was classified as loam (33% sand, 44% silt, and 23% clay), with a pH of 6.8, indicating slightly acidic-to-neutral conditions suitable for *citrus* cultivation. Phosphorus (P), magnesium (Mg), copper (Cu), iron (Fe), and manganese (Mn) levels were high, while potassium (K), calcium (Ca), and sulfur (S) were moderate. Zinc (Zn), boron (B), and ammonium nitrogen (NH_4^+) were low. The organic matter content was 1.2%, suggesting a need for improved nutrient management and fertilization.

2.4. Treatments, Experimental Design, and Experimental Unit

During the period between 2020 and 2023, two independent experimental trials were conducted, encompassing three dry-season cycles developed between August and November. In the first experiment, a factorial arrangement was used to evaluate three irrigation levels (7.77, 5.18, and 4.44 mm) combined with two concentrations of gibberellic acid (GA_3 : 80 and 200 mg L^{-1}). In the second experiment, the same irrigation levels were combined with two concentrations of auxins (NAA: 100 and 300 mg L^{-1}). The trial was established under a Randomized Complete Block Design (RCBD), with four treatments and four replications.

2.5. Application of Treatments

The plant growth regulators used in the experiments were gibberellic acid (GA_3) and 1-naphthaleneacetic acid (NAA). In the first experiment, New Giberned was applied—this is a gibberellic acid formulation with 10% *w/w* concentration, presented as a water-soluble powder. In the second experiment, NAA with a 98% purity, also in water-soluble powder form, was used.

The application of growth regulators was carried out at two specific stages of fruit development, following the BBCH scale:

- Stage I: Fruit at "ping-pong ball" stage (approximately the size of a pea).
- Stage II: Fruit reaching approximately 90% of its final size.

The growth regulator solutions were prepared using neutral pH water (pH 7.0), adjusted with a commercial water pH and hardness regulator (COSMO-AGUAS), which contains 44.5% pH-regulating citrates and 55.5% chelating edetates. Treatments were applied under cool conditions, between 7:00 and 8:00 a.m., using a two-stroke motorized backpack mist sprayer, ensuring uniform product distribution over the fruit surface.

2.6. Determination of Irrigation Levels

To determine the irrigation levels required for the lemon crop established at the “La Herradura” farm, a 10-year historical series of reference evapotranspiration (ET_0) data from the meteorological station of the National Institute of Meteorology and Hydrology (INAMHI), located at the experimental farm “La Teodomira” of the Technical University of Manabi, were used (Table 1). The study area (Finca “La Herradura”) is 13 km of linear distance from this station, with altitudinal interruptions of up to 400 m a.s.l.

Table 1. Monthly daily averages of reference evapotranspiration (ET_0 , mm/day) from a 10-year historical series of the “La Teodomira” meteorological station (Technical University of Manabí).

E	F	M	Ab	M	Jn	Jl	Ag	S	O	N	D
3.34	3.12	3.82	4.11	3.82	3.24	3.60	4.03	4.42	4.33	4.36	4.44

On the farm, the lemon plots occupy an area of 42 m², and the measurements made of the volume of water applied in the current flood irrigation management correspond to 1955.1 L, with a fixed frequency of 15 days, which is equivalent to a rainfall of 3.1 mm/day or 46.55 mm accumulated in this same period.

Irrigation Calculation Model for the Proposed Water Depths

The proposed model for calculating the net irrigation depth (NID) is based on the FAO-56 methodology [2], which expresses crop evapotranspiration (ET_c) as follows:

$$E = K_c \times ET_0$$

where $K_c = 0.7$ is the crop coefficient for lemon during the productive stage [2]; ET_0 is the reference evapotranspiration; and ET_c is the crop evapotranspiration, equivalent to the net irrigation depth.

In this study, the maximum value from the historical series was selected, $ET_0 \text{ max} = 4.44$ mm/day, to ensure full coverage of crop water demand under critical conditions. By multiplying this value by an accumulation interval (t) of 10 days, a base irrigation depth of 44.4 mm was obtained, which closely matches the local management practice (46.55 mm). This strategy allows the model to be aligned with the actual irrigation practices observed on the farm.

Subsequently, this value was multiplied by the crop coefficient (K_c), and a Variable Frequency Factor (VFF) was introduced as an operational tool to adjust the calculated net irrigation depth for different application timings within the standard 15-day interval. This adjustment simulates irrigation events occurring on days 8, 12, and 14 without modifying the actual irrigation frequency. The adjustment was implemented using the following equation:

$$NID = ET_0 \text{ max} \times K_c \times t/VFF$$

where NID is the Net Irrigation Depth to be applied (mm/day).

Finally, a correction was applied based on the irrigation method efficiency, assuming an average value of $ef = 0.5$ (50%) for flood irrigation [21], to obtain the gross irrigation depth (GID):

$$ID = NID/ef$$

Thus, three irrigation levels were defined with gross irrigation depths equivalent to those shown in Table 2, covering the range suggested by studies reported in FAO-56 [2,22,23] in other *citrus* species.

Table 2. Daily and accumulated (15-day) gross irrigation depths (GIDs) applied to a lemon crop, considering an irrigation efficiency of 50%.

Daily GID (mm/Days)	Gross Irrigation Depth (GID) Accumulated Every 15 Days of Application
7.77	116.55
5.18	77.7
4.44	66.6

2.7. Variables Evaluated

Physiological and productive variables were evaluated to determine the effect of the different treatments applied. The physiological variables included leaf water potential (Ψ_h), stomatal conductance (g_s), maximum quantum efficiency of photosystem II (F_v/F_m), and chlorophyll index. Measurements were taken at 15, 30, and 45 days after treatment application (DAT).

2.7.1. Leaf Water Potential (Ψ_h)

This variable was determined using a Scholander-type pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA), with measurements taken between 11:00 a.m. and 2:00 p.m. Young branches approximately 0.5 cm in diameter, with fully sun-exposed leaves located in the upper third of the canopy of healthy, from pest- and disease-free trees were sampled.

2.7.2. Stomatal Conductance

Stomatal conductance was recorded between 6:00 and 11:00 a.m. using a leaf porometer (SC-1 model, Decagon Devices®, Pullman, WA, USA) on fully sun-exposed leaves located in the upper third of healthy trees.

2.7.3. Maximum Quantum Efficiency of Photosystem II (F_v/F_m)

Measurements were taken using an fluorometer (OS5+ model, Opti-Sciences®, Hudson, NH, USA) between 6:00 and 7:00 a.m. on fully sun-exposed leaves in the upper canopy. Prior to measurement, leaves were dark-adapted for 30 min using dark adaptation clips to ensure accurate F_v/F_m readings. The measurements were conducted under an actinic light intensity of $1200 \mu\text{mol m}^{-2} \text{s}^{-1}$.

2.7.4. Chlorophyll Index

The relative chlorophyll index was measured using a SPAD 502-Plus chlorophyll meter (Konica Minolta®, Tokyo, Japan) on fully sunlit leaves located in the upper third of the canopy of healthy trees.

2.7.5. Fruit Yield (Kg Plant⁻¹)

To estimate fruit yield, all fruits produced per tree were harvested and weighed, and yield was expressed in kilograms per plant. Harvesting was conducted at physiological maturity, determined by external indicators such as the change in peel color from dark green to light green or yellowish hues, appropriate fruit size for the cultivar, and ease of detachment from the peduncle. Additionally, internal quality parameters, including juice content (expressed as a percentage), total soluble solids (°Brix), and titratable acidity, were assessed to ensure uniform ripeness among the samples. Yield measurements were taken under consistent environmental conditions, avoiding rainy periods to prevent excess moisture from altering fruit weight. Only healthy and marketable fruits were included in the final yield assessment, excluding any damaged or diseased specimens. Data collection was standardized during early morning hours to minimize variability due to temperature-induced fruit dehydration. In addition to yield, fruit quality traits were evaluated using a laboratory analysis of 240 fruits per treatment.

2.7.6. Polar and Equatorial Fruit Diameter (Mm)

Measurements were taken using a high-precision digital caliper (Truper®, model CALDI-14388) with a resolution of 0.01 mm to determine polar and equatorial diameters.

2.7.7. Fruit Weight (G)

Each fruit was weighed individually using a CAMRY ACS-6-ZE14 electronic balance, with results expressed in grams.

2.7.8. Pulp and Peel Weight

Pulp and peel were separated and weighed individually, using the same electronic balance.

2.7.9. Juice Content (mL) and Number of Seeds

Juice content was extracted from halved fruits, using a manual juicer, and measured in a 25 mL graduated cylinder. The number of seeds per fruit was counted manually after extraction from the pulp.

2.7.10. Total Soluble Solids (°Brix)

Total soluble solids were determined using a digital refractometer, with results expressed in degrees Brix (°Brix).

3. Results

Limes treated with auxin at 100 mg L⁻¹ showed a decrease in stomatal conductance (g_s) 30 days after irrigation treatments were applied, followed by a rapid recovery at 60 days (Figure 2A). A similar trend was observed in limes treated with 300 mg L⁻¹ of auxin (Figure 2B). In contrast, a different pattern was observed with gibberellic acid (GA₃) application, where the decrease in g_s at 15 days was minimal compared to auxin-treated plants. However, a marked recovery was evident 60 days after irrigation levels were established (Figure 1).

Regarding the behavior of the irrigation levels (Figure 1), it was observed that Irrigation Level 1 (7.77 mm) showed the fastest recovery in plants treated with auxin (Figure 2A,B), while in those treated with gibberellic acid (GA₃), the 4.44 mm irrigation level promoted better recovery. This variability in response may be attributed to the influence of the hormone and the timing of its application.

Regarding leaf water potential (ψ_h), statistically significant differences were observed 30 days after the application of irrigation treatments. However, at 45 days, lime plants irri-

gated with 4.44 mm reached values of -1.4 MPa, moving further from zero and suggesting a possible stress response, likely attributable to the irrigation level rather than the growth regulator (Figure 3A). Plants treated with GA₃ showed a trend similar to those treated with auxins (Figure 3B). However, with the application of 200 mg L^{-1} GA₃ under 5.18 and 4.44 mm irrigation levels, water potential values converged (Figure 3D), reaching values below -1.5 MPa, which may indicate full turgor in key lime.

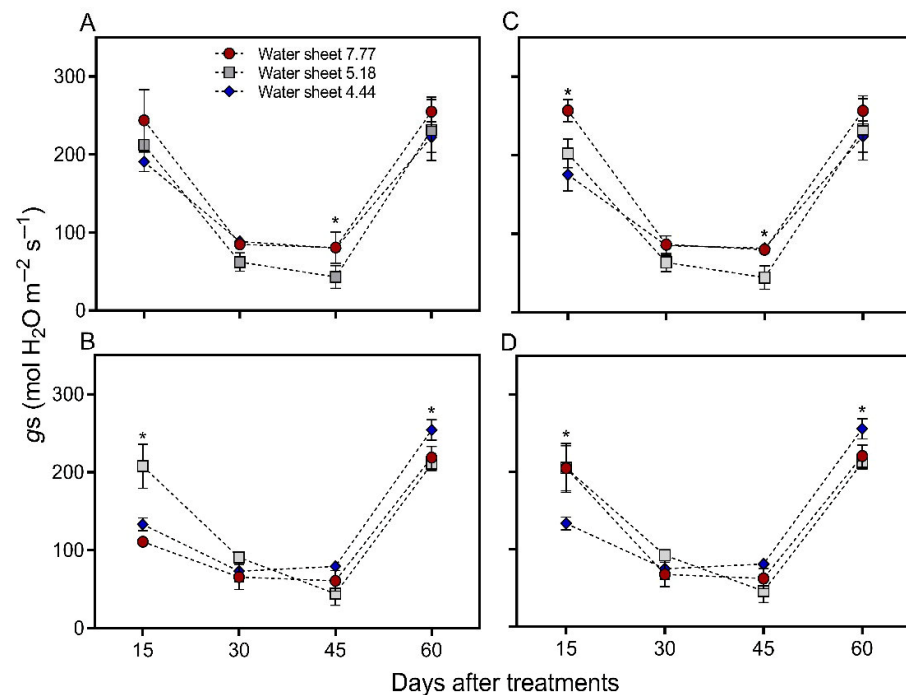


Figure 2. Effect of different irrigation levels and plant growth regulator doses on stomatal conductance in key limes. (A) Plants treated with 1-naphthaleneacetic acid at 100 mg L^{-1} , (B) 1-naphthaleneacetic acid at 300 mg L^{-1} , (C) gibberellic acid at 80 mg L^{-1} , and (D) gibberellic acid at 200 mg L^{-1} . Asterisk (*) indicates statistically significant differences among irrigation levels, according to Fisher's LSD test ($p < 0.05$).

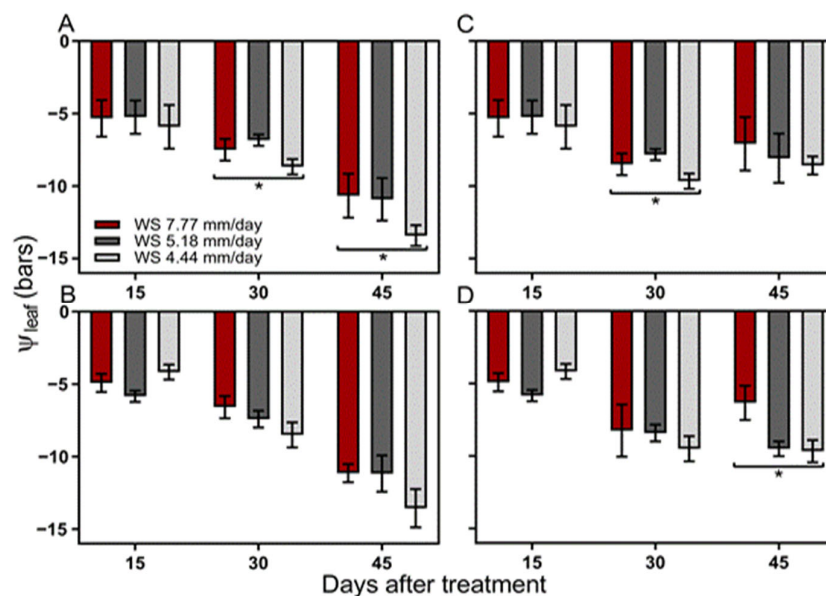


Figure 3. Leaf water potential in lime plants under different irrigation levels (WS) and growth-regulator applications. (A) Plants treated with 1-naphthaleneacetic acid at 100 mg L^{-1} , (B) 1-naphthaleneacetic acid at 300 mg L^{-1} , (C) gibberellic acid at 80 mg L^{-1} , and (D) gibberellic acid at 200 mg L^{-1} . Asterisk (*) indicates statistically significant differences among irrigation levels, according to Fisher's LSD test ($p < 0.05$).

With respect to the chlorophyll index (CI), plants treated with auxin under the 4.44 mm irrigation level showed a sharp increase during the first 30 days of evaluation (Figure 4A), which stabilized between 30 and 45 days after irrigation began, with the highest values observed under the 4.44 mm level. In contrast, when 300 mg L⁻¹ of auxin was applied (Figure 4C), the highest chlorophyll index values were recorded under the 5.18 mm level, as compared to the lower irrigation treatment.

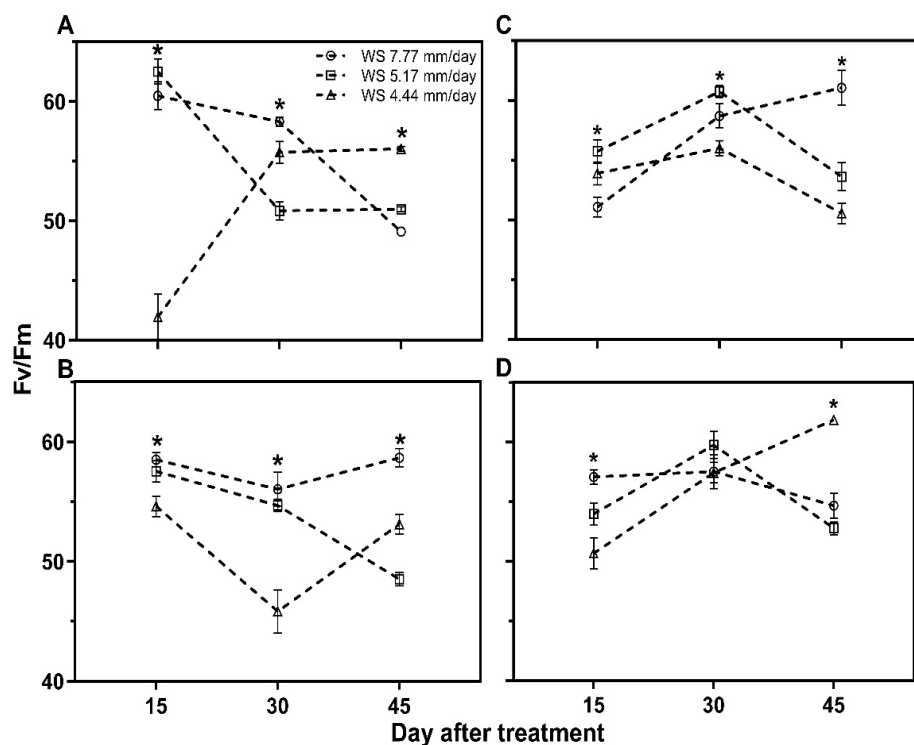


Figure 4. Quantum efficiency of photosystem II in plants treated with (A) 1-naphthaleneacetic acid at 100 mg L⁻¹, (B) 1-naphthaleneacetic acid at 300 mg L⁻¹, (C) gibberellic acid at 80 mg L⁻¹, and (D) gibberellic acid at 200 mg L⁻¹. Asterisk (*) indicates statistically significant differences among irrigation levels according to Fisher's LSD test ($p < 0.05$).

An increase in chlorophyll index was observed across all irrigation levels, with a stronger trend under the 7.77 mm treatment. This suggests that greater water availability combined with a 100 mg L⁻¹ auxin dose may favor chlorophyll production (Figure 4). Similarly, the application of 80 mg L⁻¹ GA₃ also showed an increase in chlorophyll content (Figure 4C,D). Both auxin and gibberellin appear to influence chlorophyll concentration in plants, and this effect seems to be modulated by the amount of water received (Figure 3).

Fruit Growth

Fruits with the largest polar and equatorial diameters were observed under the 7.77 mm irrigation level combined with 100 mg L⁻¹ of auxin (Figure 5A). With higher auxin concentrations, fruits irrigated with 5.18 mm reached greater polar diameters (Figure 4B). Overall, both auxins and gibberellins promoted fruit growth, and irrigation-level variability had a notable effect on the growth rate (Figure 5).

Larger fruits were obtained under the 5.18 mm irrigation level with the application of 80 mg L⁻¹ gibberellic acid, where fruits reached their maximum diameters (Figure 5C). In contrast, when the GA₃ dose was increased, a reduction in fruit growth was observed (Figure 5D).

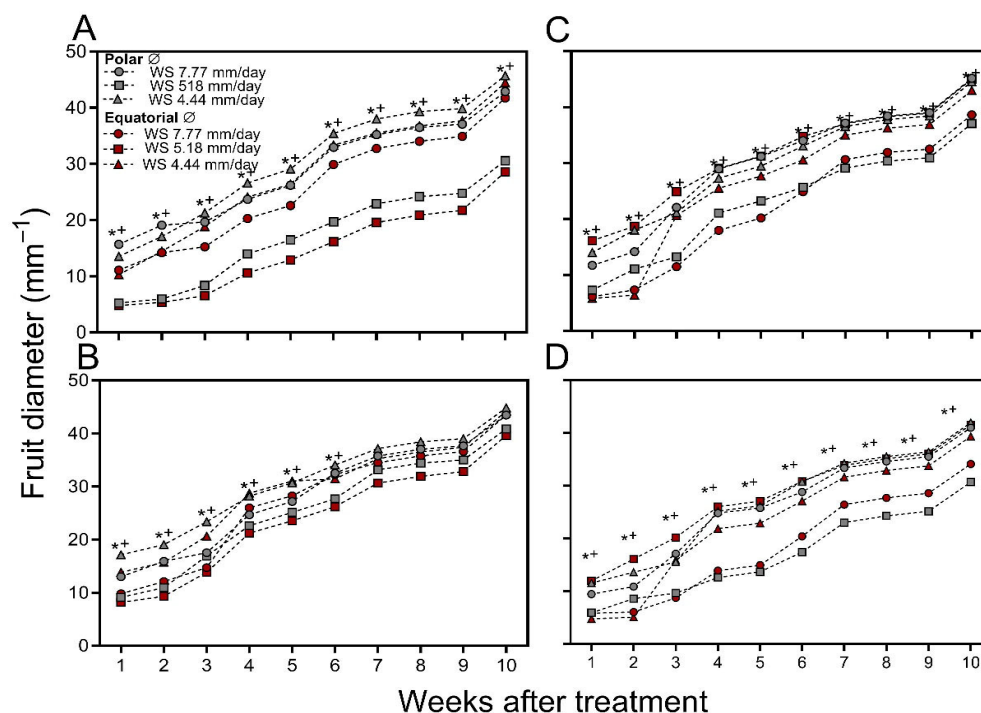


Figure 5. Polar and equatorial fruit diameter in lime plants under different irrigation levels (WS) and growth-regulator applications. (A) Plants treated with 1-naphthaleneacetic acid at 100 mg L⁻¹, (B) 1-naphthaleneacetic acid at 300 mg L⁻¹, (C) gibberellic acid at 80 mg L⁻¹, and (D) gibberellic acid at 200 mg L⁻¹. Asterisk (*) indicates statistically significant differences among irrigation levels, according to Fisher's LSD test ($p < 0.05$).

Fruits with the highest weight were obtained under the 5.18 mm irrigation level with a 100 mg L⁻¹ auxin dose, exceeding even those treated with 300 mg L⁻¹, with values reaching 50.53 ± 0.87 g. A similar trend was observed for peel weight, pulp weight, and juice content (Table 3). It is important to note that fruits irrigated with 4.44 mm showed lower juice and pulp content.

The increase in GA₃ dosage to 200 mg L⁻¹ in lime fruits led to a size increase, with values in the range of 49.20 ± 1.01 g under the 7.77 mm irrigation level. However, pulp weight and juice content were higher with the application of 80 mg L⁻¹ GA₃ under the same irrigation level. Under GA₃ treatments, the 5.18 and 4.44 mm irrigation levels did not show statistically significant differences in juice content, pulp weight, or fruit weight (Figure 6).

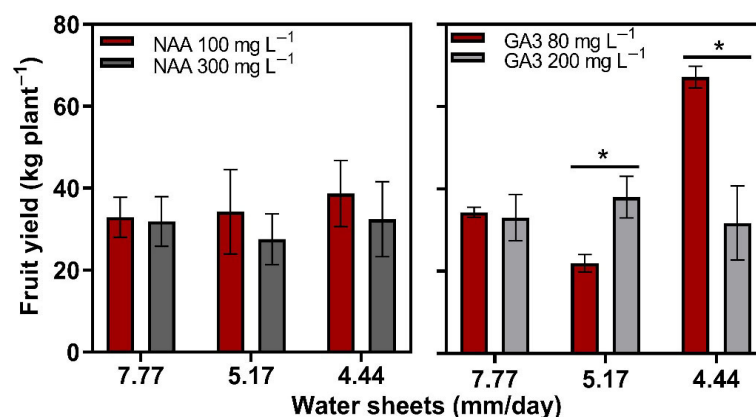


Figure 6. Effect of different irrigation levels and phytohormone doses on fruit production in key lime. NAA: 1-naphthaleneacetic acid; GA₃: gibberellic acid. Asterisk (*) indicates statistically significant differences among phytohormone doses, according to Fisher's LSD test ($p < 0.05$).

Table 3. Effect of different irrigation levels and doses of 1-naphthaleneacetic acid (NAA) on yield parameters in key lime cultivation.

Sheet Water	Yield Parameters											
	Fruit Weight (g ^{−1})		Peel Weight (g ^{−1})		Pulp Weight (g ^{−1})		Juice Content (mL)		Soluble Solids %		Number of Seeds	
	NAA 100 mg L ^{−1}	NAA 300 mg L ^{−1} ns	NAA 100 mg L ^{−1}	NAA 300 mg L ^{−1} ns	NAA 100 mg L ^{−1}	NAA 300 mg L ^{−1} ns	NAA 100 mg L ^{−1}	NAA 300 mg L ^{−1} ns	NAA 100 mg L ^{−1} ns	NAA 300 mg L ^{−1} ns	NAA 100 mg L ^{−1} ns	NAA 300 mg L ^{−1}
7.77 mm	50.53 ± 0.87 ^a	42.27 ± 2.37	30.20 ± 0.31 ^a	26.47 ± 27.60	21.80 ± 0.20 ^a	16.60 ± 1.42	21.21 ± 0.94 ^a	17.45 ± 0.83	7.99 ± 0.07	7.79 ± 0.10	5.37 + 0.07	5.30 ± 0.32 ^a
5.17 mm	41.53 ± 1.33 ^b	43.93 ± 0.97	26.07 ± 0.87 ^b	27.60 ± 0.53	15.53 ± 0.57 ^b	16.60 ± 0.83	16.47 ± 0.58 ^b	17.13 ± 0.18	7.84 ± 0.05	7.75 ± 0.02	5.77 ± 0.34	6.13 ± 0.15 ^{ab}
4.44 mm	37.60 ± 0.83 ^c	41.00 ± 1.68	23.60 ± 0.69 ^c	25.20 ± 0.92	14.30 ± 0.06 ^b	15.80 ± 0.76	14.42 ± 0.12 ^c	16.42 ± 0.88	7.64 ± 0.10	7.76 ± 0.00	6.33 ± 0.23	5.00 ± 0.35 ^b

Means followed by the same letter do not differ significantly, according to Fisher’s LSD test (*p* > 0.05). ns: non-significant differences.

In terms of yield, fruits irrigated with 7.77 mm and treated with 100 mg L⁻¹ of NAA showed the highest yield, compared to those treated with 300 mg L⁻¹, across all irrigation levels (Figure 6). The same irrigation level combined with 80 mg L⁻¹ of GA₃ also resulted in greater yield compared to other treatments, with GA₃ application producing higher yields than auxin. However, the behavior of stomatal conductance (g_s) appears to be more closely related to the irrigation levels than to the phytohormones, as observed in Figure 6.

The Figure 7 presents a multivariate analysis (PCA) that facilitates the visualization of the combined influence of irrigation depths and plant growth regulators on the most relevant physiological and productive variables evaluated. Principal Component 1 (PC1) accounted for 58.5% of the total variance in the dataset. The photochemical efficiency of Photosystem II (F_v/F_m) and the relative chlorophyll content (SPAD) exhibited a positive correlation with yield. Similarly, higher fruit weight was strongly associated with increased productivity. In contrast, a greater peel weight appeared to be linked to less favorable yield conditions. The application of NAA was associated with enhanced fruit weight and chlorophyll content, indirectly promoting yield, whereas GA₃ application seemed to exert a greater influence on photosynthetic efficiency, which also contributed positively to productivity (Figure 7A). On the other hand, the irrigation depths exerted a significant influence on the studied variables. The photochemical efficiency of Photosystem II, relative chlorophyll content, and fruit weight were positively correlated with the highest water application depth (7.77 mm/day). In contrast, lower water levels (5.18 and 4.44 mm/day) may be associated with increased stress conditions, leading, for instance, to a rise in peel weight, which ultimately resulted in lower fruit yield (Figure 7B).

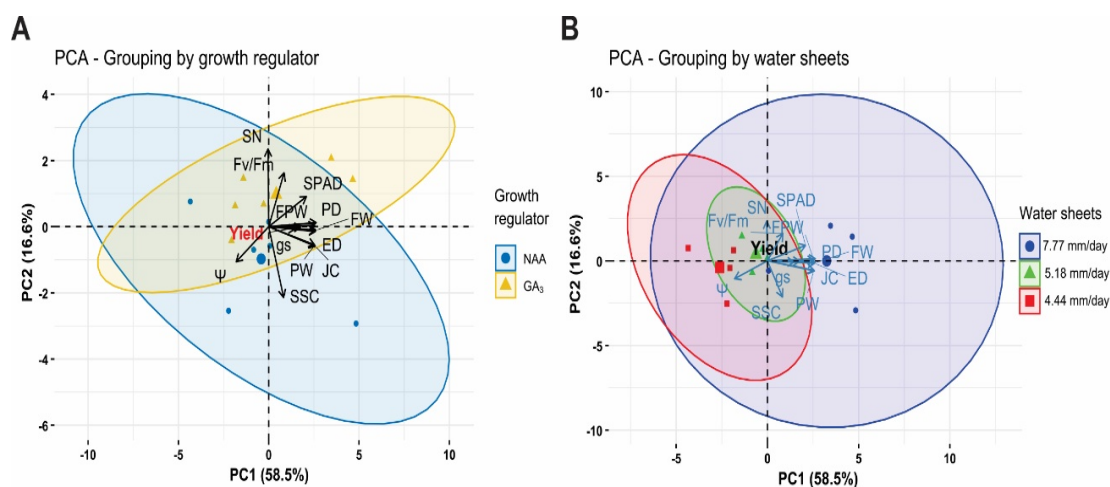


Figure 7. Principal Component Analysis (PCA). (A) Effect of growth regulators and (B) irrigation levels on physiological and yield-related variables in key lime (*Citrus aurantifolia* L.) crop. Ψ : water potential; SN: seed number; F_v/F_m : photochemical efficiency of photosystem II; SPAD: relative chlorophyll content; FPW: fruit peel weight; PD: polar diameter; ED: equatorial diameter; g_s : stomatal conductance; FW: fruit weight; JC: juice content; SSC: soluble solids content.

4. Discussion

4.1. Stomatal Conductance (g_s)

Stomatal conductance (g_s , mol H₂O m⁻² s⁻¹) in lime plants treated with different irrigation levels and growth regulators over time showed a notable decrease between 30 and 45 days (Figure 2) across all three irrigation treatments. This behavior may be associated with the plants' acclimation to soil moisture content (θ). Such adaptation is critical, given that water plays a central role in the physiological processes of crops, as emphasized by Taylor et al. [24]. This adjustment in g_s may be interpreted as a physiological response to environmental conditions, as described by Schroeder et al. [25].

Parallel research by Martínez et al. [26] in *Citrus limon* revealed a similar pattern, with reductions in both CO₂ assimilation and stomatal conductance in plants subjected to waterlogging. Additionally, Celi et al. [27] reported reduced g_s and greater sensitivity in *Citrus aurantiifolia* (key lime). These findings suggest that, based on the collected data, lime plants responded more strongly to variations in water availability than to the presence of phytohormones (Figure 2).

4.2. Leaf Water Potential (Ψ_h)

A significant correlation was found between leaf water potential (Ψ_h) and the different doses of auxin and gibberellic acid (GA₃) under varying irrigation levels (Figure 3A and 3B). Notably, under the reduced irrigation level (4.44 mm), Ψ_h values were the lowest (−1.5 MPa), observed with the application of 100 mg L^{−1} of auxin and 80 mg L^{−1} of GA₃ (Figures 3A and 3B, respectively). These results align with previous studies; Vélez et al. [28] demonstrated that water potentials between −1.5 and −2.0 MPa do not prevent normal fruit growth, highlighting the plasticity of certain plants under drought stress conditions.

The role of auxins and gibberellins in activating signaling pathways that modulate stress resistance is well supported, as noted by Iqbal et al. [13], and is reflected in stomatal regulation a key physiological response to environmental fluctuations [29]. According to Buckley [30], water potential is a major determinant of stomatal behavior, a finding confirmed in the present study (Figure 3). Stomatal conductance (g_s) decreased in response to the applied irrigation levels; however, this trend appeared to be independent of Ψ_h , suggesting that other intrinsic or environmental factors may be influencing g_s (Figure 2). In the case of stomatal conductance (g_s), recent studies have shown that abscisic acid (ABA) plays a central role in modulating stomatal conductance under water deficit, triggering signaling pathways involving oxidative stress responses and calcium influx in guard cells; this supports the idea that the observed changes in Ψ_h , g_s , and chlorophyll index may be mediated by specific hormonal pathways activated under limited water availability. Rai et al. [31] and Sezena et al. [32] emphasized the influence of soil water content (θ) on g_s , where reduced water availability leads to a decline (Figure 2). Considering the irrigation regime, the observed decrease in g_s (Figure 2) may reflect an adaptive mechanism, possibly triggered by an oversupply of water relative to the crop's actual demand (Table 2). Water distribution likely adjusted progressively according to soil moisture content [32].

4.3. Chlorophyll Index

The chlorophyll index, measured in SPAD units, showed an increase at 15 days. However, these values dropped below 40 under the lowest irrigation level (4.4 mm), as shown in Figure 4A. After 45 days from the application of the irrigation treatments, a rise in the chlorophyll index was observed, particularly when 100 mg L^{−1} of auxin was applied, together with 4.44 mm of irrigation. This increase was even more pronounced under the 7.77 mm irrigation level, where 300 mg L^{−1} of auxin and the lowest concentration of gibberellic acid were applied, showing a notable improvement (Figure 4B,C). Previous studies in Italian lemon (*Citrus limon* [L.] Osbeck) using iron chelates reported increases in the chlorophyll index, with leaf greenness values ranging between 39 and 47 [33]. These results are lower than those obtained in the present study (Figure 4), which ranged from 42 to 65. This difference may be attributed to the synergistic effect of auxin and gibberellin on chlorophyll biosynthesis, as evidenced in Figure 4.

4.4. Quantum Efficiency of Photosystem II

Higher irrigation levels led to increased fruit diameters (Figure 5) [34], with auxin and gibberellin activity also contributing to this response (Figure 5) in the case of the independent trials [35]. Although variations in hormone levels throughout fruit development have

been studied in woody species such as *citrus*, the specific dynamics of interaction between gibberellins (GA) and auxins during the fruit set stage require further investigation [36,37]. The increase in fruit diameter observed in Figure 5 A–C,D over time highlights the effectiveness of these growth regulators. This effect is modulated by irrigation, confirming its crucial role in maximizing crop yield. These results support the application of auxins and gibberellins [38] as enhancers of fruit development in agricultural practices, particularly when associated with environmental conditions [39] and water use efficiency [40]. However, a deficient irrigation regime negatively affects fruit size, including both polar and equatorial diameters (Figure 5), an observation which aligns with the trends observed in this study. As noted by [41], reduced irrigation can impact radial and equatorial growth, underscoring the importance of water management strategies in fruit production.

4.5. Fruit Quality

Fruit weight under different irrigation regimes and auxin doses (Figure 5), as well as gibberellin applications (Figure 6), shows that under higher irrigation conditions (7.77 mm), there was a significant increase in fruit weight, pulp weight, and juice content when 100 mg L⁻¹ of auxin was applied. This response is likely associated with cell expansion [42] and overall fruit growth [43].

As shown in Table 3, fruits irrigated with 7.77 mm and treated with 100 mg L⁻¹ of NAA exhibited the highest values for fruit weight, peel weight, pulp weight, and juice content, even surpassing the 300 mg L⁻¹ dose. This indicates that a moderate auxin dose under optimal irrigation enhances fruit development [2]. In contrast, the 4.44 mm irrigation level significantly reduced these traits, highlighting the role of water in hormonal transport and assimilate distribution (Taiz et al. [44]; Choudhary et al. [17]). Soluble solids were slightly higher under the lowest irrigation level, likely due to solute concentration effects (Fawole & Opara, [45]; Yahia et al. [46]). Peel weight and seed number remained unaffected by auxin dose, suggesting a saturation response under water-limited conditions, as described in Table 3.

In contrast, with GA₃ application under the same high irrigation level (7.77 mm), both concentrations of GA₃ produced similar effects, with no significant differences observed in fruit weight, peel, pulp, or juice content. These findings suggest that, under optimal water availability, gibberellins may reach a threshold of effectiveness even at lower concentrations. Unlike the auxin treatments, which showed more pronounced differences among doses, gibberellins appeared to produce consistent responses. Studies in Kinnow mandarin also highlight the importance of GA₃ in fruit expansion and juice accumulation [47]. Fruit development is regulated by plant growth regulators at each of its phenological stages [48,49].

4.6. Yield

The effects of phytohormones also appear to be influenced by the amount of available water (Figure 6). Under optimal irrigation conditions (7.77 mm), plants likely had sufficient water resources to support the action of gibberellins, resulting in increased yield. In contrast, under lower irrigation levels, although a slight increase was observed with the higher GA₃ dose, it was not statistically significant (Figure 6), suggesting a threshold of water stress below which the beneficial effects of gibberellins are mitigated [50]. Gibberellins are known to promote the growth of various plant tissues, including fruits [51]. Their exogenous application has been reported to improve fruit quality and size in several crops [52], contributing to their rising commercial importance in recent years [53].

The effects of hormones are influenced by the amount of available water. In this context, water availability (Figure 6) may facilitate the mobilization of resources, including gibberellins, to promote yield [54], as reflected in the highest irrigation level (7.77 mm). In

the present study, the high auxin dose (200 mg L^{-1}) did not produce significant effects under any irrigation level, which may be associated with the role of auxins in cell elongation [55], and thus more directly related to fruit diameter than to total yield. Auxins may also influence physiological processes, particularly respiration and photosynthesis, leading to the accumulation of dry matter, minerals, and carbohydrates [56]. Therefore, the proper use of auxins is essential to ensure that fruits reach commercially acceptable sizes without compromising overall production [57].

The results obtained with auxin application (Figure 6) are consistent with the findings of Guerra et al. [58], who reported that a reduction in water availability ($L3 = 50\%$ of ET_0) could not be compensated by auxin application in terms of fruit yield [36]. Although auxins are generally used to promote fruit set and growth, their effectiveness may be limited under low water availability conditions (Figure 6). In contrast, additional applications of gibberellic acid (GA_3) resulted in larger fruits, which are more desirable in the market [59]. Similarly, in *citrus* crops, GA_3 treatments have shown multiple beneficial effects, including increases in fruit weight and overall yield [60].

4.7. Principal Component Analysis (PCA)

Principal Component Analysis (PCA, Figure 7) revealed that irrigation at 7.77 mm combined with moderate doses of NAA (100 mg L^{-1}) and GA_3 (80 mg L^{-1}) enhanced photosystem II photochemical efficiency (F_v/F_m), relative chlorophyll content (SPAD), and fruit weight, resulting in higher yields [34,38]. Conversely, higher concentrations of NAA (200 mg L^{-1}) and GA_3 (160 mg L^{-1}), particularly under water-limited conditions (4.44 mm), were associated with reduced leaf water potential (-1.5 MPa) and negative impacts on photosynthetic performance [26], respiration [57], and biomass accumulation [51], leading to a metabolic shift toward non-commercial structures such as peel tissue (Table 4) [12,28]. These findings are consistent with those of Guerra et al. [58], who reported that under deficit irrigation ($50\% ET_0$), auxin application did not offset yield losses. Additionally, studies in *citrus* suggest that excessive gibberellin concentrations may reach a saturation threshold, beyond which no further benefits are observed, and detrimental effects on fruit growth and quality may occur [60,61].

Table 4. Effect of different irrigation levels and doses of gibberellic acid (GA₃) on yield parameters in key lime cultivation.

Sheet Water	Yield Parameters											
	Fruit Weight (g ⁻¹)		Peel Weight (g ⁻¹)		Pulp Weight (g ⁻¹)		Juice Content (mL)		Soluble Solids %		Number of Seeds	
	GA ₃ 80 mg L ⁻¹	GA ₃ 200 mg L ⁻¹	GA ₃ 80 mg L ⁻¹	GA ₃ 200 mg L ⁻¹	GA ₃ 80 mg L ⁻¹	GA ₃ 200 mg L ⁻¹	GA ₃ 80 mg L ⁻¹	GA ₃ 200 mg L ⁻¹	GA ₃ 80 mg L ⁻¹ ns	GA ₃ 200 mg L ⁻¹ ns	GA ₃ 80 mg L ⁻¹ ns	GA ₃ 200 mg L ⁻¹ ns
7.77 mm	48.33 ± 2.02 ^a	49.20 ± 1.01 ^a	28.67 ± 0.37 ^a	30.27 ± 0.64 ^a	19.67 ± 1.65 ^a	18.93 ± 0.37 ^a	19.45 ± 1.05 ^a	19.18 ± 0.30 ^a	7.66 ± 0.11	7.60 ± 0.06	6.17 ± 0.24	6.40 ± 0.21
5.17 mm	40.67 ± 0.07 ^b	42.47 ± 0.82 ^b	25.87 ± 0.24 ^b	26.00 ± 0.23 ^b	14.80 ± 0.20 ^b	16.47 ± 0.59 ^b	15.70 ± 0.15 ^b	16.32 ± 0.66 ^b	7.65 ± 0.05	7.79 ± 0.02	6.13 ± 0.12	6.37 ± 0.26
4.44 mm	41.07 ± 0.18 ^b	40.07 ± 1.05 ^b	25.47 ± 0.33 ^b	24.73 ± 0.71 ^c	15.60 ± 0.50 ^b	15.33 ± 0.37 ^b	15.45 ± 0.46 ^b	15.52 ± 0.38 ^b	7.59 ± 0.02	7.74 ± 0.03	6.23 ± 0.24	5.77 ± 0.20

Means followed by the same letter are not significantly different, according to Fisher's LSD test ($p > 0.05$). ns: non-significant differences.

5. Conclusions

The combination of controlled irrigation (7.77 mm) with moderate doses of NAA (100 mg L⁻¹) and GA₃ (80 mg L⁻¹) significantly improved the physiological performance and yield of key lime. In contrast, higher hormone doses under water stress reduced efficiency and productivity. These findings support integrated strategies of irrigation and phytohormone application to optimize productivity under semi-arid conditions.

6. Recommendation

Since irrigation depth and growth regulator doses significantly affect the yield and physiological responses of key lime (*Citrus aurantiifolia*), it is recommended to apply regulated deficit irrigation combined with moderate doses of NAA (100 mg L⁻¹) and GA₃ (80 mg L⁻¹) to enhance fruit production under semi-arid conditions. Future studies should evaluate the long-term effects of high hormone doses under water stress and their interaction with key environmental factors.

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