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Yield and economics of carrot [*Daucus carota* (L.)] genotypes as affected by water management and Gibberellic Acid in a changing climate

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Abstract

Carrot is a high-value crop, but its productivity and profitability depend on water management, genotype selection, and plant growth regulators like gibberellic acid (GA_3). This study examined the interactive effects of these factors on carrot yield and economic returns at two locations: Research and Teaching farm of Bayero University Kano (BUK) and a community demonstration farm at Maida during the 2019/2020 and 2020/2021 cold dry seasons. A split-plot design was used, testing four irrigation intervals (farmer's practice, 5, 7, and 9 days), two genotypes (Touchon Mega and Griffaton), and four GA_3 application rates (100 ppm applied once, twice, or three times, and a control). Results showed that frequent irrigation (farmer's practice, W1) and the 5-day interval (W2) significantly improved yield, net income, and benefit-cost ratio (BCR) at both locations ($P < 0.001$). The highest yield was recorded under W1V1G1 at BUK (23,417 kg/ha) and Maida (23,183 kg/ha), with net incomes of ₦6,161,001 and ₦6,183,732, respectively, and a BCR exceeding 6.0. In contrast, the 9-day interval (W4) led to severe yield reductions and financial losses, with the lowest net income observed under W4V2G4 at Maida (₦227,900, BCR 0.18) and BUK (₦277,000, BCR 0.24). Touchon Mega (V1) consistently outperformed Griffaton (V2), confirming its suitability for high-yield, high-profitability carrot farming. Similarly, GA_3 application (100 ppm × 3) significantly enhanced yield and economic returns, while the control (no GA_3) had the lowest profitability. The study concluded that integrating optimized irrigation, superior genotype selection, and GA_3 application maximizes both productivity and financial sustainability in carrot production.

Keywords*: Irrigation scheduling, Carrot production, Economic profitability, Genotypic performance, Growth regulators*

Introduction

Carrot (*Daucus carota* L.) is an economically important root vegetable grown worldwide, providing essential nutrients and contributing significantly to the agricultural sector (Eze *et al.*, 2024; Zubair *et al.*, 2024). Carrots hold significant economic value due to their high demand in fresh markets, processing industries, and export trade. They are rich in beta-carotene, vitamins, and antioxidants, making them essential for health-conscious consumers (Ghani *et al.*, 2021; Eze et al., 2024). Carrot farming also provides employment opportunities across the supply chain, from production to retail (Pethybridge *et al.*, 2023). Additionally, the processing industry benefits from carrot-based products such as juices, baby food, and frozen goods, adding value to agricultural produce (Colquhoun *et al.,* 2020).

Carrots contribute substantially to agricultural revenue, with major producers including China, the United States, and Russia (Wang *et al.,* 2015). Their adaptability to diverse climatic conditions and soil types further enhances their economic significance, making them a viable crop for sustainable agricultural enterprises (Umar *et al.,* 2024). However, climate change, characterized by erratic rainfall patterns, prolonged droughts, and rising temperatures, threatens their yield and economic viability (Umar *et al.,* 2024).

Effective water management practices are crucial in mitigating these adverse effects and ensuring sustainable carrot production. Plant growth regulators such as gibberellic acid (GA_3) has been found to enhance growth and yield in several crops under various environmental conditions (Ghani *et al*., 2021). Plants respond to environmental stresses through physiological adaptations, including osmotic adjustments and hormonal regulation (Miri *et al*., 2021). GA_3 plays a critical role in modulating these responses by promoting cell elongation, enzyme activation, and photosynthetic efficiency, which could enhance carrot growth under water-limited conditions (Wang *et al*., 2017; Tang *et al*., 2024).

Despite these advances, limited research exists on the interactive effects of water management and GA_3 application on different carrot genotypes. Addressing this gap is essential for optimizing both productivity and economic returns under changing climatic conditions. Integrating effective water management strategies with GA_3 application not only sustains carrot productivity but also strengthens its economic potential in global markets. Sustainable agriculture necessitates the optimization of inputs, such as water and growth regulators, to achieve maximum yield with minimal environmental impact (Dawar *et al.,* 2020). By evaluating the interaction between irrigation regimes and GA_3 application, this study aligns with agronomic principles aimed at resource-efficient crop production. Crop profitability is influenced by yield output, input costs, and marketability (Pethybridge *et al.,* 2023). Thus, assessing the cost-effectiveness of different water management and GA_3 treatments will go a long way in determining carrot farming. Therefore, this study was carried out with the aim of evaluating water management strategies, GA_3 application rates, and their impact on carrot genotypes, morphology, economic returns, and ultimately identifying the most cost-effective combination for optimizing carrot production in a changing climatic scenario.

Materials and Methods

Experimental sites

Field trials were carried out during the dry season of 2020 and 2021 at two different locations: Teaching and Research farm, Faculty of Agriculture, Bayero University Kano hereinafter referred to BUK (Lat. 11^o 58' N and Long. 8^o 26' E, 475m asl) and community-based farm at Maida Village, Garko Local Government area of Kano State referred to Maida (Lat. 10^o 10' 30.22'' N and Long. 11^o 09' 52.49" E, 458 m asl). Both locations are situated in the Sudan savanna Agroecological zone of Nigeria (Kowal and Knabe, 1972). The soils at both BUK and Maida were classified as sandy loam, with slight variations in physical and chemical properties across the two seasons. Maida's soil had higher organic carbon (0.96 g/kg) and available phosphorus (8.56 mg/kg), suggesting slightly better fertility compared to BUK (0.69 g/kg organic carbon, 7.99 mg/kg available P). However, BUK recorded higher cation exchange capacity (CEC) (6.33 cmol/kg) than Maida (6.04 cmol/kg), indicating better nutrient retention. These variations align with findings by Ashine et al. (2024), which emphasize that soil texture and nutrient availability significantly influence crop productivity.

Treatments and experimental design

The experiment comprised four water management regimes: W1 (farmer practice, 5 days at early vegetative stage, 7 days at juvenile to pre-flowering stage, and 9 days at post-flowering to maturity stage), W2 (all irrigation at 5-day intervals), W3 (all irrigation at 7-day intervals), W4 (all irrigation at 9-day intervals as control), two varieties (V1=Touchon Mega and V2=Griffaton), and four application periods of GA3 (G1: 100 ppm at vegetative stage, 100 ppm at flowering stage, and 100 ppm at rooting stage; G2: 100 ppm at vegetative and 100 ppm at flowering stage; G3: 100 ppm at flowering stage; and G4: 0 ppm as control). These were factorially combined and laid out in a split-split plot design and replicated three times with water management regimes allocated to the main plot variety to the subplots and GA_3 to the sub-subplots.

Preparation of growth regulators

A growth regulator in the form of gibberellic acid (GA_3) at the rate of 1 g was dissolved in drops of NaOH (10N), and the volume was filled up to 1000 mL of distilled water. Thereafter, GA_3 solutions were prepared for foliar spraying with concentrations of 0, 50, and 100 ppm. These concentrations were sprayed once on the plants when they attained a 4-6 leaf stage.

Cultural practices

Land preparation

The experimental site was ploughed and double harrowed to obtain a fine tilth while organic manure was incorporated into the soil during the process. A furrow of 0.75 m in between a strip of 2 m was dug and used as a distributor channel. The strips were later encircled with raised bunds into a basin of 2 m length.

Sowing

Seeds were sown directly on the raised basins of 1.2 x 2m using a recommended spacing of 20 cm between and within rows, after which the beds were mulched with rice straws but were removed after seeding emergence.

Fertilization

Fertilizer was applied at the rate of 65 kg N, 45 kg P_2O_5, and 45 kg K_2O/ha using NPK 15:15:15, which was basally applied at 2 weeks after sowing (WAS) to supply 300 kg/ha, which was followed by top dressing urea 50 kg/ha at 5 WAS.

Weeding

Weeds were properly managed by hand weeding twice at 3 and 7 WAS.

Data collection and data analysis

Data were collected on root length, root diameter, root fresh weight, and yield using standard agronomic procedures, and measurement of weight-related attributes was done using a digital weighing balance (Mettler Toledo PM 4000). All data collected were subjected to analysis of variance (ANOVA) as described by Snedecor and Cochran (1967) using Genstat (17th edition). Significant treatment means were separated using the Student Newman-Keuls test (SNK) at a 5% probability level. Additionally, the profitability of carrot production under the different treatments was analyzed using cost-benefit analysis (CBA), gross margin analysis, and benefit-cost ratio (BCR). The following economic indicators were computed: Total Variable Cost (TVC): Includes cost of seeds, fertilizers, agrochemicals (GA_3), irrigation, labor, and other inputs used in carrot production. Costs were recorded based on market prices during the experimental period.

Total Fixed Cost (TFC): Includes costs related to land preparation, depreciation of equipment, and rental costs (where applicable).

Total Cost of Production (TCP): Computed as:

$$TCP = TVC + TFC \text{--Equa. 1}$$

Gross Revenue (GR) (₦/ha): Calculated as:

$$GR = Yield\ (\text{ kg/ha })x\ Market\ price\ ((\text{?}/\text{ha}) \text{ --------------------------Equa. 2}$$

The market price of carrot was set at ₦300/kg, based on average market rates during the study period.

Net Revenue (NR) or Net Farm Income (NFI) (₦/ha): Computed as:

$$NR = GR - TCP \text{---Equa. 3}$$

Benefit-Cost Ratio (BCR**):** Evaluates the financial viability of each treatment and is given by:

$$BCR = \frac{Gross\ Revenue}{Total\ Cost\ of\ Production} \text{------------------------------Equa. 4}$$

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A BCR greater than 1.5 is considered economically viable, while a BCR below 1.0 indicates financial loss (Razvi, 2023).

Results and Discussion

Root Length (cm)

The influence of water management (WM) and gibberellic acid (GA_3) on carrot root length during the 2019/2020 and 2020/2021 dry seasons is shown in Table 1. Results indicate that WM and GA_3 significantly affected root length at BUK and Maida. More frequent irrigation (farmer's practice) produced the longest roots, while increased irrigation intervals (5, 7, and 9 days) reduced root length. Touchon Mega exhibited superior root length compared to Griffaton across all sampling periods. GA_3 application (100 ppm × 3) significantly enhanced root length, while the control treatment resulted in the shortest roots. Interaction effects (WM × G, WM × GA_3, and G × GA_3) were highly significant ($P < 0.001$), confirming that optimal root development depends on irrigation, genotype selection, and GA_3 application. The three-way interaction (WM × G × GA_3) was also significant, emphasizing the importance of integrating these factors for optimal results.

Table 1: Root Length per plant (cm) of Carrot genotypes as Affected by Water management and Gibberellic Acid at BUK and Maida during the 2019/2020 and 2020/2021 Dry Seasons

	BUK						Maida					
	2019/2020		2020/2021		Combined		2019/2020		2020/2021		Combined	
	Weeks after sowing (WAS)											
Treatment	12	15	12	15	12	15	12	15	12	15	12	15
Water management (WM)												
Farmer practice	14.17[a]	20.76a	16.13a	22.74a	15.15a	21.75a	15.96a	23.48a	14.10a	20.30a	15.03a	21.89a
5 days	11.45b	18.20b	12.73b	20.84b	12.09b	19.52b	14.31b	22.35b	12.51b	20.93a	13.41b	21.64b
7 days	8.19c	11.95c	8.90c	14.79c	8.54c	13.37c	11.62c	16.62c	9.18c	14.45b	10.40c	15.54c
9 days	7.14d	6.05d	6.46d	8.96d	6.80d	7.51d	8.54d	10.96d	5.79d	7.51c	7.16d	9.24d
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.078	0.106	0.117	0.240	0.039	0.053	0.298	0.325	0.757	0.671	0.640	0.180
Genotype (G)												
Touchon Mega	10.73a	17.07a	11.82a	17.96a	11.27a	17.51a	13.73a	19.89a	11.81a	17.96a	12.77a	18.93a
Griffaton	9.74b	11.41b	10.29b	15.70b	10.02b	13.56b	11.49b	16.81b	8.97b	13.64b	10.23b	15.22b
Prob > F	0.004	<.001	0.001	0.014	<.001	<.001	0.016	0.088	0.011	0.011	<.001	<.001
SE (±)	0.179	0.682	0.218	0.509	0.141	0.426	0.912	0.218	0.601	0.925	0.304	0.463
Gibrelic Acid (GA_3)												
100ppm x3	15.23a	19.05a	22.21a	4.47a	14.68a	20.63a	14.64a	22.30a	14.74a	22.25a	14.69a	22.28a
100ppmx2	10.61b	16.33b	20.01b	3.98b	11.62b	18.17b	13.85b	21.06b	11.80b	18.21b	12.83b	19.64b
100ppmx1	9.08c	13.59c	15.80c	3.38c	9.83c	14.69c	12.67c	18.41c	9.63c	14.64c	11.15c	16.53c
Control	6.04d	8.00d	9.30d	2.68d	6.46d	8.65d	9.27d	11.64d	5.41d	8.09d	7.34d	9.86d
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.098	0.270	0.133	0.026	0.069	0.151	0.054	0.032	0.056	0.081	0.028	0.041
Interaction												
WM × V	<.001	0.082	0.074	0.119	<.001	<.001	<.001	0.312	0.371	0.519	0.440	0.271
WM × GA_3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
V × GA_3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
WM × V × GA_3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level of significance.

Root Diameter per Plant (cm)

Table 2 presents the impact of WM and GA_3 on root diameter. WM and GA_3 significantly influenced root diameter at both locations. The largest root diameters were observed under the farmer's practice, decreasing with increased irrigation intervals. Touchon Mega exhibited significantly ($P < 0.001$) larger diameters than Griffaton, highlighting genetic differences in root expansion. GA_3 application (100 ppm × 3) significantly increased root diameter, while the control resulted in the smallest measurements. Significant ($P < 0.001$) interactions (WM × G, WM × GA_3, and G × GA_3) confirm that root diameter is influenced by a combination of water availability, genotype selection, and GA_3 application. The three-way interaction further underscores the importance of integrating these agronomic factors.

Table 2: Root diameter per plant (cm) of Carrot genotypes as Affected by Water management and Gibberellic Acid at BUK and Maida during the 2019/2020 and 2020/2021 Dry Seasons

Treatment	BUK 2019/2020		BUK 2020/2021		BUK Combined		Maida 2019/2020		Maida 2020/2021		Maida Combined	
	Weeks after sowing (WAS)											
	12	15	12	15	12	15	12	15	12	15	12	15
Water management (WM)												
Farmer practice	10.46a	12.48a	10.52a	12.97a	10.49a	12.72a	10.02a	11.62b	10.78a	13.56a	10.40a	12.59a
5 days	9.46b	11.27b	8.96b	11.75b	9.21b	11.51b	9.29b	11.76a	8.97b	12.06b	9.13b	11.91b
7 days	7.38c	9.20c	8.33b	9.98c	7.86c	9.59c	2.44d	2.94d	8.21c	10.58c	5.33c	6.76c
9 days	5.17d	7.09d	5.43c	6.42d	5.30d	6.75d	5.49c	6.85c	5.06d	6.01d	5.28c	6.43d
Prob > F	<.001	<.001	0.003	0.009	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.068	0.087	1.255	1.566	0,034	0.043	0.801	0.771	0.297	0.478	0.479	0.524
Genotype (G)												
Touchon Mega	9.36a	11.47a	9.43a	11.64a	9.38a	11.55a	7.45a	8.86a	9.58a	12.06a	8.52a	10.46a
Griffaton	6.90b	8.55b	7.19b	8.92b	7.05b	8.73b	6.16b	7.72b	6.94b	9.04b	6.55b	8.38b
Prob > F	<.001	0.105	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.309	0.388	0.273	0.413	0.206	0.246	0.698	0.881	0.339	0.419	0.69	0.209
Gibrelic Acid (GA_3)												
100ppm x3	10.43a	12.61a	11.44a	13.67a	10.93a	13.14a	8.38a	10.88a	10.86a	14.02a	9.62a	12.45a
100ppmx2	9.42b	11.02b	9.31b	11.38b	9.36b	11.20b	8.12b	9.49b	9.10b	11.54b	8.62b	10.51b
100ppmx1	7.27c	9.64c	7.52c	9.63c	7.86c	9.64c	6.01c	7.40c	7.51c	9.37c	6.76c	8.39c
Control	5.36d	6.76d	4.97d	6.43d	5.30d	6.59d	4.72d	5.40d	5.55d	7.27d	5.13d	6.34d
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.100	0.115	0.064	0.148	0.059	0.058	0.910	0.932	0.041	0.012	0.021	0.011
Interaction												
I × V	0.022	0.104	0.122	0.013	0.002	0.004	<.001	<.001	0.062	0.101	<.001	0.002
I × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
V × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
I×V × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level of significance.

Root Fresh Weight per Plant (g)

Table 3 illustrates the effect of WM and GA_3 on root fresh weight. The 5-day irrigation interval produced the highest biomass, followed by the farmer's practice, while longer intervals (7 and 9 days) significantly reduced fresh weight. Touchon Mega exhibited superior biomass accumulation compared to Griffaton, suggesting genetic advantages in resource utilization and stress resilience. GA_3 application (100 ppm × 3) significantly increased biomass, while the control had the lowest accumulation. The interactions (WM × G, WM × GA_3, and G × GA_3) were highly significant ($P < 0.001$), highlighting the combined influence of irrigation, genotype, and GA_3 application on biomass production.

Carrot Yield (kg ha⁻¹)

Table 4 shows that WM, GA_3, and genotype significantly influenced carrot yield across both seasons and locations. The highest yields were observed under the farmer's practice, followed by the 5-day irrigation interval, with yield declining at 7 and 9-day intervals. Touchon Mega significantly ($P < 0.001$) outperformed Griffaton in yield, demonstrating superior adaptability. GA_3 application (100 ppm × 3) significantly enhanced yield, while the control had the lowest yields, indicating GA_3 role in promoting carrot growth and productivity.

Table 3: Root fresh weight per plant (g) of Carrot genotypes as Affected by Water management and Gibberellic Acid at BUK and Maida during the 2019/2020 and 2020/2021 Dry Seasons

Treatment	BUK						Maida					
	2019/2020		2020/2021		Combined		2019/2020		2020/2021		Combined	
	Weeks after sowing (WAS)											
	12	15	12	15	12	15	12	15	12	15	12	15
Water management (WM)												
Farmer practice	32.43^{b}	59.39^{b}	32.51^{a}	60.45^{a}	32.47^{b}	59.92^{b}	28.11^{b}	53.07^{a}	28.81^{b}	61.20^{a}	28.46^{a}	57.14^{a}
5 days	35.65^{a}	67.02^{a}	32.09^{a}	58.89^{b}	33.87^{a}	62.96^{a}	31.80^{a}	44.41^{b}	31.03^{a}	56.05^{b}	31.42^{b}	57.73^{a}
7 days	27.73^{c}	50.64^{c}	20.73^{b}	37.50^{c}	24.23^{c}	44.07^{c}	10.31^{c}	15.37^{c}	20.11^{c}	26.56^{c}	15.21^{c}	20.96^{b}
9 days	13.57^{d}	17.75^{d}	9.43^{c}	15.13^{d}	11.51^{d}	16.44^{d}	10.23^{c}	13.41^{d}	9.34^{d}	12.26^{d}	9.73^{d}	12.83^{c}
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.260	0.596	0.158	0.158	0.637	0.383	0.194	0.78	0.154	0.108	0.177	1.787
Genotype (G)												
Touchon Mega	31.08^{a}	52.86^{a}	27.78^{a}	50.01^{a}	29.43^{a}	51.44^{a}	22.03^{a}	35.32^{a}	24.74^{a}	43.16^{a}	23.38^{a}	28.62^{a}
Griffaton	23.61^{b}	44.54^{b}	19.60^{b}	35.98^{b}	21.60^{b}	40.26^{b}	18.20^{b}	32.68^{b}	19.86^{b}	34.87^{b}	19.03^{b}	33.77^{b}
Prob > F	<.001	<.001	<.001	0.007	<.001	<.001	0.108	0.003	<.001	<.001	<.001	<.001
SE (±)	0.199	0.632	0.905	2.748	0.463	1.410	0.689	2.606	0.031	0.156	0.016	0.000
Gibrelic Acid (GA_3)												
100ppm x3	36.60$_{a}$	65.96^{a}	33.61^{a}	63.61^{a}	35.11^{a}	64.78^{a}	27.43^{a}	46.33^{a}	30.89^{a}	60.38^{a}	29.16^{a}	56.99^{a}
100ppmx2	32.39^{b}	59.20^{b}	27.55^{b}	51.98^{b}	29.97^{b}	55.59^{b}	24.01^{b}	43.03^{b}	25.97^{b}	45.70^{b}	24.99^{b}	44.37^{b}
100ppmx1	26.56^{c}	46.50^{c}	22.21^{c}	40.95^{c}	24.39^{c}	43.73^{c}	19.48^{c}	30.43^{c}	20.72^{c}	34.10^{c}	20.10^{c}	32.26^{c}
Control	13.83^{d}	23.15^{d}	11.11^{d}	15.43^{d}	12.62^{d}	19.29^{d}	9.53^{d}	14.37^{d}	11.61^{d}	15.88^{d}	10.57^{d}	15.12^{d}
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	0.383	0.928	0.238	0.639	0.225	0.563	0.317	1.119	0.150	0.264	0.075	0.132
Interaction												
I × V	<.001	<.001	0.014	0.013	<.001	0.006	<.001	0.015	<.001	<.001	0.202	<.001
I × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
V × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.403	<.001	<.001	<.001	<.001
I×V × GA3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.009	<.001	<.001	<.001	<.001

Means within a column of treatment followed by unlike letter (s) are significantly different at 5% level of significance using SNK.

The superior root length, root diameter, root fresh weight, and yield observed under the farmer's irrigation practice can be attributed to enhanced water availability and nutrient uptake, promoting deeper root growth. This finding aligns with Umar *et al.* (2024). Similarly, optimizing irrigation frequency significantly enhances root development, as also reported by Ashine *et al.* (2024), who found that supplementary irrigation improved carrot root growth. The observed increase in root dimensions suggests that frequent irrigation facilitates water and nutrient uptake, which is crucial for root expansion and overall physiological processes, further supporting the findings of Umar *et al.* (2024).

Table 4: Yield (kg/ha) of Carrot varieties as Affected by Water management and Gibberellic at BUK and Maida during the 2019/2020 and 2020/2021 Dry Seasons.

Treatment	BUK		Maida		Combined	
	2019/2020	2020/2021	2019/2020	2020/2021	BUK	Maida
Water management (WM)						
Farmer practice	14,490a	16,190a	16,170a	13,830a	15,340a	15,000a
5 days	13,690b	14,630b	14,680b	13,360b	14,160b	14,020b
7 days	8,240c	9,890c	9,420c	7,790c	9,060c	8,600c
9 days	6,490d	5,890d	5,890d	5,320d	6,190d	5.61d
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	16.3	19.4	541.6	255.3	9.7	0.5
Genotype (G)						
Touchon Mega	12,350a	12,950a	12,780a	11,850a	12,650a	12,300a
Griffaton	91,100b	10,340b	10,300b	8,330b	9,730b	9,320b
Prob > F	<.001	0.019	0.012	<.001	<.001	<.001
SE (±)	204.8	633.1	2.420	1.00	332.7	299.4
Gibrelic Acid (GA_3)						
100ppm x3	14,470a	15,540a	15,330a	13,980a	14,980a	14,650a
100ppmx2	11,340b	13,530b	13,310b	10,790b	12,440b	12,050b
100ppmx1	9,690c	10,560c	10,490c	8,970c	10,130c	9,730c
Control	7,470d	6,960d	7,030d	6,570d	7,210d	6,800d
Prob > F	<.001	<.001	<.001	<.001	<.001	<.001
SE (±)	68.8	136.6	131.9	35.0	76.5	68.2
Interaction						
WM × V	<.001	0.934	<.001	<.001	<.001	0.042
WM × GA_3	<.001	<.001	<.001	<.001	<.001	<.001
V × GA_3	<.001	<.001	<.001	<.001	<.001	<.001
WM × V × GA_3	<.001	<.001	0.002	<.001	<.001	<.001

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level of significance.

Table 5: Interaction between Water management and Variety on Carrot Yield (kg/ha^{-1}) at BUK during the 2019/2020 Dry Season.

	BUK		Maida	
	Variety			
Treatment	Touchon Mega	Griffaton	Touchon Mega	Griffaton
Water management				
Farmer practice	17,790a	11,190c	17,790a	11,190d
5 days	16,090b	11,290c	16,090b	11,290c
7 days	8,530d	7,950d	8,530e	7,950f
9 days	6,990e	6,010e	6,990g	6,010h
SE (±)	409.5		409.5	

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level of significance.

Touchon Mega significantly outperformed Griffaton in growth and yield, highlighting the role of genetic factors in root elongation. This aligns with Pethybridge *et al*. (2023), who reported genotypic variations in carrot response to growth regulators and environmental conditions. Selecting cultivars with superior root elongation traits, such as Touchon Mega, could enhance productivity under different environmental conditions, as supported by Colquhoun *et al.* (2020). However, this contradicts Zubair K *et al.* (2024), who found Griffaton to be superior in their study.

Table 6: Interaction between Water management and Gibberellic Acid (GA_3) on Carrot Yield (kg/ha^{-1}) at BUK during the 2019/2020 and 2020/2021 Dry Seasons.

	GA_3							
	2019/2020				2020/2021			
Treatment	100ppmx3	100ppmx2	100ppmx1	Control	100ppmx3	100ppmx2	100ppmx1	Control
Water management				BUK				
Farmer practice	20,690a	15,140c	12,780e	9,370h	21,430a	18,7000c	157,00e	8,920i
5 days	19,070b	13,890d	12,110f	9,700h	19,830b	16,660d	12,100g	9,901h
7 days	10,100g	8,340i	7,930j	6,580k	13,120f	11,450g	9,480hi	5,500k
9 days	7,8500j	7,980j	5,950l	4,220m	7,800j	7,330j	4,970k	3,490l
SE (±)		137.6				237.3		
				Maida				
Farmer practice	21,530a	18,750b	15,740d	8,650g	20,340a	14,420c	12,130e	8,440i
5 days	19,230b	16,820c	12,380e	10,300f	18,210b	13,930d	11,650f	9,660h
7 days	12,830e	10,460f	8,980g	5,390i	10.130g	8,000j	7,680k	5,350n
9 days	7,710h	7,210h	4,880i	3,770j	7,220l	6,800m	4,400o	2,870p
SE (±)		263.8.6				260.7		

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level.

Table 7: Interaction between Variety and Gibberellic Acid (GA3) on Carrot Yield (kg/ha^{-1}) at BUK and Maida during the 2019/2020 and 2020/2021 Dry Seasons.

Treatment	Variety			
	2019/2020		2020/2021	
		BUK		
GA_3	Touchon Mega	Griffaton	Touchon Mega	Griffaton
100ppm x3	15,830a	13,030c	17,010a	14,070bc
100ppmx2	13,850b	8,830e	14,660b	12,400d
100ppmx1	11,330d	8,060f	12,310c	8.820e
Control	8,390ef	6,530g	7,830ef	6,080f
SE (±)	221.4		654.8	
		Maida		
100ppm x3	16,770a	14,470b	16,890a	10,770c
100ppmx2	6,210e	13,880b	15,670b	11,050c
100ppmx1	12,150c	12,030c	8,150d	7,430de
Control	8,970d	7,840e	6,580e	4,060f
SE (±)	1083.2		510.7	

Means within a column of treatment followed by unlike letter (s) are significantly different using SNK at 5% level of significance.

The significant positive impact of GA_3 100 ppm × 3 on root length, root diameter, root fresh weight, and yield highlights its role in promoting cell elongation, nutrient mobilization, root-shoot development, and photosynthetic efficiency (Ghani *et al.*, 2021). Its influence on root biomass and elongation is well documented (Wang *et al.*, 2023; Schuler and Colquhoun, 2022). El-Tohamy *et al.* (2023) also reported GA_3's role in improving plant performance under optimized water management. However, excessive GA_3 application may reduce root diameter and overall biomass, emphasizing the need for optimal concentration and application frequency (Pethybridge *et al.*, 2023).

Table 8: Economic profitability of Carrot production as influenced by Water management, Variety and Gibberellic Acid at BUK during the 2019/2020 and 2020/2021 Dry Seasons (Combined)

Water management	Variety	GA_3	Yield (kg ha^{-1})	Total Cost (TVC + TFC)	Gross revenue (₦/kg)	Net Revenue (₦/kg)	Net income (₦)	BCR
W1	V2	G4	8,200	924,000	300	2,460,000	1,596,000	1.66
W1	V2	G3	8,517	936,000	300	2,555,000	1,691,000	1.73
W1	V2	G1	17,967	973,350	300	5,390,001	4,526,001	4.54
W1	V2	G2	10,100	936,000	300	3,030,000	2,166,000	2.24
W1	V1	G1	23,417	973,350	300	7,025,001	6,161,001	6.22
W1	V1	G3	17,050	936,000	300	5,115,000	4,251,000	4.46
W1	V1	G4	10,533	924,000	300	3,159,999	2,295,999	2.42
W1	V1	G2	20,183	948,000	300	6,054,999	5,190,999	5.39
W2	V2	G3	9,450	956,000	300	2,835,000	1,951,000	1.97
W2	V2	G1	17,933	993,350	300	5,379,999	4,495,999	4.42
W2	V2	G4	7,650	944,000	300	2,295,000	1,411,000	1.43
W2	V2	G2	10,133	968,000	300	3,039,999	2,155,999	2.14
W2	V1	G3	14,767	956,000	300	4,430,001	3,546,001	3.63
W2	V1	G4	11,750	944,000	300	3,525,000	2,641,000	2.73
W2	V1	G2	17,650	968,000	300	5,295,000	4,411,000	4.47
W2	V1	G1	20,200	993,350	300	6,060,000	5,176,000	5.10
W4	V2	G2	7,050	932,000	300	2,115,000	1,267,000	1.27
W4	V2	G1	6,633	957,350	300	1,990,000	1,142,000	1.08
W4	V2	G4	3,750	908,000	300	1,125,000	277,000	0.24
W4	V2	G3	6,600	920,000	300	1,980,000	1,132,000	1.15
W4	V1	G1	9,067	957,350	300	2,720,000	1,872,000	1.84
W4	V1	G4	4,683	908,000	300	1,405,000	557,000	0.55
W4	V1	G2	8,900	932,000	300	2,670,000	1,822,000	1.86
W4	V1	G3	5,300	920,000	300	1,590,000	742,000	0.73
W3	V2	G3	7,117	944,000	300	2,135,000	1,275,000	1.26
W3	V2	G1	8,517	969,350	300	2,555,000	1,695,000	1.64
W3	V2	G4	6,417	920,000	300	1,925,000	1,065,000	1.09
W3	V2	G2	7,417	932,000	300	2,225,000	1,365,000	1.39
W3	V1	G2	9,267	944,000	300	2,780,000	1,920,000	1.94
W3	V1	G4	6,733	920,000	300	2,020,000	1,160,000	1.20
W3	V1	G1	11,683	969,350	300	3,504,999	2,644,999	2.62

W1= Farmer practice, W2= 5 days, W3=7 days, W4= 9 days (Water management levels through irrigation scheduling); V1= Touchon Mega, V2= Griffaton;
G1= 100ppm x3, G2=100ppm x2, G3=100ppm x1, G4=Control (no GA_3); BCR= Benefit cost ratio.; TVC= Total variable cost; TFC=Total fixed cost.

Interaction Effects

Significant ($P < 0.001$) interactions (WM × G, WM × GA_3, and G × GA_3) confirm that carrot yield is influenced by irrigation frequency, genotype selection, and GA_3 application. Table 5 highlights that the farmer's practice combined with Touchon Mega resulted in the highest yield. Table 6 indicates that frequent irrigation with GA_3 application (100 ppm × 3) significantly increased yield, while the 9-day irrigation interval with no GA3 had the lowest yield. Table 7 shows that Touchon Mega combined with GA_3 (100 ppm × 3) resulted in higher yields compared to the Griffaton in control, confirming the consistency of this trend across seasons and locations.

The significant two-way (WM × V, V × GA_3, WM × GA_3) and three-way (WM × V × GA_3) interactions indicate that yield optimization requires an integrated approach. These findings align with studies highlighting the importance of irrigation in maintaining optimal carrot growth and yield (Ciza *et al.,* 2022). Tang *et al.* (2024) also reported that combining optimized water management with variety selection improves carrot yield and quality. Similarly, prior research underscores the benefits of integrating multiple management strategies to enhance productivity (Colquhoun *et al.*, 2020).

Economic Analysis of Carrot Production

The profitability of carrot production under different water management (WM), genotype, and GA_3 application scenarios is presented in Tables 8 and 9. The farmer's practice (W1) resulted in the highest net income and benefit-cost ratio (BCR) at both locations, with the most profitable treatment (W1V1G1) yielding 23,417 kg/ha. This treatment generated net incomes of ₦6,161,001 (BCR 6.22) at BUK and ₦6,183,732 (BCR 6.24) at Maida, emphasizing the economic benefits of integrating optimal irrigation, genotype selection, and GA3 application. Conversely, increasing irrigation intervals (W2, W3, W4) led to reduced yield and profitability, with the least profitable treatment (W4V2G4) recording net incomes of ₦277,000 (BCR 0.24) at BUK and ₦227,900 (BCR 0.18) at Maida. This highlights the negative financial impact of poor water management, suboptimal genotype selection, and lack of growth regulation.

The application of 100 ppm × 3 (G1) resulted in the highest net income and BCR at both locations, confirming GA_3's role in enhancing yield and financial viability. This aligns with findings by Silva et al. (2021), who reported that optimized irrigation and fertilization significantly increased carrot yield and economic returns. Farmers who adopted frequent irrigation (W1, W2), high-yielding varieties (Touchon Mega – V1), and GA_3 achieved substantial net gains, with BCR values exceeding 4.0 in most cases. Similar economic benefits were observed in organic carrot farming, where improved agronomic practices boosted profitability (Souza e Souza *et al*., 2023).

The best-performing treatment, W1V1G1, recorded the highest BCR (6.22 at BUK, 6.24 at Maida), indicating that for every ₦1 invested, farmers gained ₦6.22 and ₦6.24, respectively. This underscores the high return on investment associated with optimal irrigation, superior genotype selection, and GA_3 application. A comparable trend was observed in seed priming studies, where improved seed quality and growth enhancements increased net returns (Sharma *et al.,* 2020). Conversely, the control treatment (G4) had the lowest net income and BCR, further highlighting GA_3's importance in maximizing profitability. The least profitable treatment, W4V2G4, showed significant financial losses, consistent with Zec et al. (2022), who reported reduced revenue from suboptimal production techniques.

A comparative analysis of the two locations reveals that while Maida had slightly higher net income in top-performing treatments, it also experienced greater financial losses in the worst-performing ones. This suggests that carrot production in Maida is more vulnerable to drought than in BUK. The lower yields and financial returns under W4 underscore the importance of efficient water management in mitigating climate-induced risks. These findings align with Ashine et al. (2024), who found that optimizing supplementary irrigation enhances productivity and reduces financial risks in water-limited conditions. Similarly, Pinto et al. (2023) reported that economic profitability in carrot farming depends on irrigation efficiency, agronomic inputs, and genotype selection, all of which influence net revenue and cost-benefit outcomes. These findings reinforce the need for integrating multiple agronomic practices to maximize carrot productivity and profitability.

Table 9: Economic profitability of Carrot production as influenced by Water management, Variety and Gibberellic Acid at Maida during the 2019/2020 and 2020/2021 Dry Seasons (Combined)

Water management	Variety	GA_3	Yield (kg ha^{-1})	Total cost (TVC + TFC)	Gross revenue (₦/kg)	Net revenue (₦/kg)	Net income (₦)	BCR
W1	V2	G4	6,933	924,000	300	2,080,000	1,216,000	1.25
W1	V2	G3	14,233	936,000	301	4,284,232	3,420,232	3.58
W1	V2	G1	19,883	973,350	302	6,004,766	5,140,766	5.17
W1	V2	G2	17,433	936,000	303	5,282,299	4,418,299	4.64
W1	V1	G1	23,183	973,350	304	7,047,732	6,183,732	6.24
W1	V1	G3	17,250	936,000	305	5,261,250	4,397,250	4.62
W1	V1	G4	10,367	924,000	306	3,172,201	2,308,201	2.43
W1	V1	G2	20,067	948,000	307	6,160,468	5,296,468	5.50
W2	V2	G3	9,567	956,000	308	2,946,533	2,062,533	2.08
W2	V2	G1	17,583	993,350	309	5,433,249	4,549,249	4.47
W2	V2	G4	9,567	944,000	310	2,965,667	2,081,667	2.14
W2	V2	G2	15,617	968,000	311	4,856,784	3,972,784	4.02
W2	V1	G3	15,200	956,000	312	4,742,400	3,858,400	3.96
W2	V1	G4	11,033	944,000	313	3,453,432	2,569,432	2.66
W2	V1	G2	18,017	968,000	314	5,657,234	4,773,234	4.84
W2	V1	G1	20,867	993,350	315	6,573,001	5,689,001	5.62
W4	V2	G2	5,783	932,000	316	1,827,533	979,533	0.96
W4	V2	G1	6,517	957,350	317	2,065,783	1,217,783	1.16
W4	V2	G4	3,383	908,000	318	1,075,900	227,900	0.18
W4	V2	G3	3,733	920,000	319	1,190,933	342,933	0.29
W4	V1	G1	8,900	957,350	320	2,848,000	2,000,000	1.97
W4	V1	G4	4,150	908,000	321	1,332,150	484,150	0.47
W4	V1	G2	8,633	932,000	322	2,779,933	1,931,933	1.98
W4	V1	G3	6,033	920,000	323	1,948,767	1,100,767	1.12
W3	V2	G3	7,033	932,000	324	2,278,800	1,418,800	1.45
W3	V2	G1	8,950	969,350	325	2,908,750	2,048,750	2.00
W3	V2	G4	4,133	920,000	326	1,347,467	487,467	0.46
W3	V2	G2	8,350	944,000	327	2,730,450	1,870,450	1.89
W3	V1	G2	12,567	944,000	328	4,121,868	3,261,868	3.37
W3	V1	G4	6,650	920,000	329	2,187,850	1,327,850	1.38
W3	V1	G1	16,717	969,350	330	5,516,501	4,656,501	4.69
W3	V1	G3	10,917	932,000	331	3,613,418	2,753,418	2.88

W1= Farmer practice, W2= 5 days, W3=7 days, W4= 9 days (Water management levels through irrigation scheduling); V1= Touchon Mega, V2= Griffaton;
G1= 100ppm x3, G2=100ppm x2, G3=100ppm x1, G4=Control (no GA_3); BCR= Benefit cost ratio; TVC= Total variable cost; TFC=Total fixed cost.

Conclusion and Recommendation

The findings confirm that frequent irrigation (W1 and W2), high-yielding genotypes (Touchon Mega), and GA_3 application (100 ppm × 3) significantly improve carrot production profitability at both BUK and Maida. The best-performing treatment, W1V1G1, resulted in the highest net income (₦6,161,001 at BUK and ₦6,183,732 at Maida) and the highest BCR (6.22 and 6.24, respectively), indicating excellent investment efficiency. Conversely, extended irrigation intervals (W4) and suboptimal genotype selection (V2-Griffaton) led to drastic financial losses, with W4V2G4 yielding the lowest net income (₦227,900 at Maida, ₦277,000 at BUK) and a BCR below 1.0, confirming economic unviability. These results highlight the critical role of efficient irrigation, appropriate genotype selection, and plant growth regulation in ensuring sustainable and profitable carrot production. Maida recorded slightly higher economic returns under optimal conditions, but it also showed greater losses under water stress, suggesting that Maida's carrot production is more vulnerable to prolonged drought than BUK. Therefore, additional soil moisture conservation strategies (such as mulching) should be considered in Maida to mitigate water stress effects.

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