

Growth, phenological response, and yield of cucumber as influenced by variety, plant spacing and NPK fertilizer rate under tropical conditions

Falaiye, O. O.¹, Adeyemi, N. O.², Oni, O. E.², Somoye R. A.², Kasali A. O.³, Falaiye O. M.² & Adekunle E. A.²

¹Centre of Excellence in Agricultural Development and Sustainable Environment (CEADESE),
Federal University of Agriculture, Abeokuta (FUNAAB), Ogun State, Nigeria

²Department of Plant Physiology and Crop Production, Federal University of Agriculture, Abeokuta (FUNAAB), Ogun State, Nigeria

³Department of Agriculture and Agricultural Technology, The Bells University, Ota, Ogun State, Nigeria

Author for correspondence: falaiyeoo@funaab.edu.ng

Summary: Cucumber (*Cucumis sativus* L.) is the fourth most cultivated vegetable globally and an increasingly important cash crop in Nigeria. Yield stagnation from suboptimal variety selection, inappropriate plant spacing and inadequate fertiliser management constrains smallholder productivity in the humid tropics. This study determined the optimal combination of variety, plant spacing and NPK 15-15-15 fertiliser rate for maximising growth and fruit yield under tropical field conditions in the forest-savanna transition zone of SW Nigeria. Two field trials were conducted at FUNAAB (7°15'N, 3°25'E) in 2019 and 2020 using a split-split plot RCBD with three replications, evaluating two varieties (CU 999 and Monalisa), three plant spacings (75×25, 75×50, 75×75 cm) and four NPK rates (0, 100, 200, 300 kg ha⁻¹). Variety CU 999 produced significantly higher fruit yield (up to 9.18 t ha⁻¹) than Monalisa across all trials. Plants at 75×25 cm spacing consistently achieved the highest yield per hectare. NPK at 300 kg ha⁻¹ reduced days to 50% flowering by 3.8–6.4 days and increased yield across trials. The three-way interaction (Variety × Spacing × Fertiliser) was significant for fruit yield, with CU 999 × 75×25 cm × 300 kg ha⁻¹ recording peak performance. CU 999 sown at 75×25 cm and fertilised with 300 kg ha⁻¹ NPK 15-15-15 is recommended for maximum cucumber yield in the forest-savanna transition zone of Nigeria.

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Introduction

Cucumber (*Cucumis sativus* L.) ranks fourth among the most cultivated vegetables globally and occupies an increasingly strategic position in Nigeria's horticulture sector (Tatlioglu, 1997; Gruda et al., 2017; FAOSTAT, 2022.). It is a rich source of vitamins A, C, K and B-complex, potassium, dietary fibre and antioxidant phytochemicals, making it nutritionally and medicinally valuable to Nigerian consumers (Olaniyi et al., 2009; Kumar et al., 2010). Despite rising urban demand, domestic cucumber productivity remains constrained by poor variety selection, suboptimal agronomic management and declining soil fertility a consequence of shortened fallow periods on heavily cultivated peri-urban farms (Ayoola & Adeniran, 2006; Nweke et al., 2013).

Plant spacing regulates inter-plant competition for light, water and nutrients and has a direct bearing on vine growth, flowering, fruit morphology and marketable yield (Nnoke, 2001; Serquen et al., 1997). Close spacing is generally associated with higher per-unit-area yields but can suppress individual plant performance, while wide spacing encourages vigorous vegetative growth at the expense of population productivity (Nerson, 1998; Ding et al., 2022). Recent greenhouse studies by Ding et al. (2022) confirmed that reducing plant density improved per-plant yield and photosynthetic efficiency in cucumber without sacrificing total area yield under protected conditions, though this outcome may

differ markedly under tropical open-field conditions where solar radiation is non-limiting and pest pressure is greater.

Balanced NPK fertilisation is equally indispensable because soils in the forest-savanna transition zone of SW Nigeria are characteristically low in organic matter and available macronutrients (Ayoola & Adeniran, 2006). Nitrogen drives vegetative growth and chlorophyll synthesis; phosphorus supports root proliferation and early reproductive development; and potassium regulates photosynthate partitioning, osmoregulation and fruit quality (Ehiokhilen & Remison et al. (2023) demonstrated in an open-field study in Qatar that nitrogen application at the recommended rate of 100 kg N ha⁻¹ under drip irrigation significantly increased cucumber yield, with yield declining at sub-optimal N levels a finding that underscores the universal importance of adequate macronutrient supply regardless of environment. Similarly, Acharya et al. (2024) reported in Nepal that a combination of FYM and balanced NPK fertilisation under mulched conditions produced the highest cucumber growth and yield, attributing this to improved water retention and sustained nutrient availability.

Varietal performance interacts strongly with both spacing and fertiliser application (Chotangui et al., 2022; Falaiye et al., 2022). Multi-factor field evaluations that simultaneously account for genotype, plant density and fertility management are, however, scarce for tropical Nigeria. Falaiye et al. (2022),

reporting from the same agro-ecological zone as the present study, documented significant spacing \times variety interactions on cucumber growth and phenology, reinforcing the need for variety-specific agronomic recommendations. The present study extends that work by incorporating fertiliser rate as a third treatment factor and by replicating across four trials over two seasons, generating robust data for practical recommendation.

We hypothesized that variety selection, plant spacing, and NPK fertilizer rate would significantly and interactively influence the growth, phenological development, and marketable yield of cucumber under tropical field conditions. The specific objectives were to: (i) evaluate the growth and phenological response of two cucumber varieties to plant spacing and NPK rate; (ii) determine yield components and fruit yield across treatment combinations; and (iii) identify the optimal variety-spacing-fertiliser combination for maximum cucumber productivity in the SW Nigerian forest-savanna transition zone.

Materials and methods

Experimental site and seasonal conditions

Field trials were conducted at the Teaching and Research Farm of DUFARMS, FUNAAB (latitude 7°15'N, longitude 3°25'E; altitude 144 m a.s.l.) in the forest-savanna transition agro-ecological zone of SW Nigeria. The rainfall regime is bimodal with peaks in July and September; totals were 1,413.2 mm in 2019 and 1,017.3 mm in 2020. Pre-planting soil analysis confirmed a sandy loam texture (74–76% sand), slightly acidic to near-neutral pH (6.8–7.2), low organic carbon (0.48–0.72%) and low available phosphorus (19.6–26.5 mg kg⁻¹), characteristic of intensively cropped peri-urban soils in SW Nigeria.

Treatments and experimental design

Treatments comprised two cucumber varieties CU 999 and Monalisa three plant spacings: 75 cm \times 25 cm (53,333 plants ha⁻¹), 75 cm \times 50 cm (26,667 plants ha⁻¹) and 75 cm \times 75 cm (17,778 plants ha⁻¹), and four NPK 15-15-15 rates: 0, 100, 200 and 300 kg ha⁻¹. These were arranged as a split-split plot in an RCBD with three replications; variety = main plot, spacing = sub-plot, fertiliser = sub-sub-plot. Sub-sub-plot size was 2 m \times 2 m. Trials I (early season) and II (late season) were conducted in each of 2019 and 2020.

Agronomic practices

Seeds were sown directly on raised beds. Seedlings were thinned to one per hole at 1 WAS; vacant stands were resupplied at the same time. NPK 15-15-15 was applied by side placement at 2 WAS. Standard cultural practices (manual weeding, pest and disease scouting) were applied uniformly across all plots throughout the growing season.

Data collection

Five randomly selected, tagged plants per plot provided all measurements. Parameters collected included: primary vine length (cm) at 3, 4, 5 WAS; leaf number per plant at 3, 4, 5

WAS; leaf area (cm²) using the validated regression model $Y = 12.9X - 54.31$ ($r^2 = 0.97$) based on leaf breadth (Adedokun & Aiyelaagbe, 2004) at 3 and 6 WAS; days to 50% flowering; days to fruit set; fruit girth (mm) and fruit length (cm) measured on five fruits per picking; unit fruit weight (g); number of fruits per plant; and cumulative fruit yield (t ha⁻¹).

Statistical analysis

Data were subjected to ANOVA for a split-split plot design and means separated by LSD at $P \leq 0.05$. Additional analyses PCA of yield-component variables, polynomial regression of yield on NPK rate, and interaction heatmaps were conducted in Python 3.11 (scikit-learn, scipy, matplotlib, numpy, pandas libraries).

Results

Pre-plant soil and seasonal weather

Soil texture was sandy loam with pH 6.8–7.2, low organic carbon (0.48–0.72%) and moderate available P (19.6–26.5 mg kg⁻¹). Total annual rainfall was higher in 2019 (1,413.2 mm) than 2020 (1,017.3 mm), with contrasting monthly distributions. Maximum temperatures peaked in November in both years (32.1 and 35.5 °C respectively).

Primary vine length

Monalisa produced longer vines than CU 999 in Trial I of 2019 at all WAS (LSD = 0.004–1.80; **Table 1**), while CU 999 outperformed Monalisa in Trial II of 2020 (LSD = 0.47–4.41). This environment-dependent varietal ordering indicates a genotype \times environment interaction that is explored further in the Discussion. Spacing at 75 \times 75 cm consistently promoted the longest vines in both 2019 (Trial I, 5 WAS: 415.6 vs. 358.7 cm at 75 \times 25 cm; LSD = 3.34) and Trial I of 2020, reflecting reduced inter-plant competition for light and nutrients under wider rows. NPK at 300 kg ha⁻¹ significantly increased vine length in Trial I of 2019 and in both trials of 2020 (e.g., Trial I 2020 at 5 WAS: 126.1 vs. 98.0 cm for 300 vs. 0 kg ha⁻¹; LSD = 12.65), consistent with nitrogen-mediated stimulation of meristematic activity and auxin-driven stem elongation (**Figure 2b**).

Number of leaves and leaf area

In Trial I of 2019, Monalisa had significantly more leaves per plant than CU 999 at 3 and 4 WAS (13.24 vs. 11.39; LSD = 0.001). Spacing of 75 \times 75 cm consistently supported the highest leaf counts at 5 WAS (45.3 vs. 39.6 at 75 \times 25 cm in Trial I 2019; LSD = 0.075). NPK at 300 kg ha⁻¹ produced significantly more leaves than the control in all trials where fertiliser effects were significant (**Table 1**). Leaf area at 6 WAS was larger in CU 999 than Monalisa in Trials I and II of 2019 (193.0 vs. 174.0 cm² in Trial I; LSD = 25.01) and Trial I of 2020 (157.3 vs. 139.3 cm²; LSD = 17.57). Fertiliser at 300 kg ha⁻¹ consistently produced the largest leaf areas across all trials (**Table 2**); the spacing \times fertiliser interaction revealed the 75 \times 75 cm \times 300 kg ha⁻¹ combination as optimal for leaf expansion (**Figures 2c, 2d**).

Table 1. Effect of variety, spacing and NPK fertiliser rate on primary vine length (cm) and number of leaves per plant of cucumber at 3, 4 and 5 weeks after sowing (WAS) in both trials of 2019 and 2020.

Treatment	2019						2020					
	Trial I			Trial II			Trial I			Trial II		
	3 WAS	4 WAS	5 WAS	3 WAS	4 WAS	5 WAS	3 WAS	4 WAS	5 WAS	3 WAS	4 WAS	5 WAS
Variety												
CU 999	27.32	169.94	343.58	20.41	58.23	112.96	17.18	53.91	120.29	11.16	30.00	69.93
Monalisa	31.69	216.44	430.01	24.39	74.20	125.43	17.15	49.37	112.03	10.47	26.98	58.16
LSD	0.004	0.691	1.801	ns	ns	ns	ns	ns	ns	0.471	4.405	ns
Spacing												
75 × 25 cm	28.09	177.86	358.68	22.07	74.75	129.93	17.17	45.38	103.45	9.90	25.05	56.80
75 × 50 cm	29.45	193.01	386.10	22.31	68.12	122.31	16.98	54.10	120.43	11.05	29.02	62.20
75 × 75 cm	30.96	208.68	415.60	22.82	55.78	105.30	17.35	55.45	124.60	11.49	31.40	73.13
LSD	0.166	1.009	3.342	ns	ns	ns	ns	ns	13.846	ns	ns	15.127
NPK rate (kg ha⁻¹)												
0	28.97	186.97	376.28	22.60	58.39	93.91	13.73	41.77	97.98	9.95	24.50	48.86
100	29.15	191.45	380.52	21.92	74.33	130.16	17.99	54.32	120.39	10.58	28.92	66.75
200	29.71	194.98	391.14	21.37	61.13	130.84	18.24	54.30	120.21	10.55	29.06	66.17
300	30.18	199.34	399.22	23.72	71.03	121.86	18.71	56.18	126.06	12.18	31.49	74.40
LSD	0.615	1.073	4.542	ns	ns	ns	0.764	6.600	12.648	1.435	4.614	7.295

ns = not significant. LSD ($P \leq 0.05$)**Table 2.** Effect of variety, spacing and NPK fertiliser rate on leaf area (cm²) at 3 and 6 WAS in both trials of 2019 and 2020.

Treatment	2019 Trial I		2019 Trial II		2020 Trial I		2020 Trial II	
	3 WAS	6 WAS	3 WAS	6 WAS	3 WAS	6 WAS	3 WAS	6 WAS
Variety								
CU 999	98.48	193.01	59.47	168.10	119.60	157.26	59.46	132.00
Monalisa	100.42	174.02	60.51	118.90	115.50	139.32	60.39	127.50
LSD	ns	25.012	ns	22.550	ns	17.568	ns	ns
Spacing								
75 × 25 cm	98.42	184.93	58.63	119.90	111.70	131.99	50.16	123.00
75 × 50 cm	110.39	183.92	61.35	166.80	121.00	152.41	59.36	129.40
75 × 75 cm	89.54	182.50	60.00	143.80	120.00	161.28	70.25	136.80
LSD	ns	ns	ns	2.230	ns	9.070	14.011	10.560
NPK rate (kg ha⁻¹)								
0	89.98	170.83	55.98	119.80	105.60	134.20	52.08	106.50
100	96.64	182.60	58.00	149.80	120.00	151.66	63.24	134.90
200	104.76	180.36	61.14	158.00	120.00	154.46	57.96	132.20
300	106.43	200.29	64.85	146.50	124.70	152.85	66.43	145.20
LSD	12.194	18.899	4.577	12.350	8.130	8.263	9.376	11.670

ns = not significant. LSD ($P \leq 0.05$)

Table 3. Effect of variety, spacing and NPK fertiliser rate on days to 50% flowering and days to fruit set of cucumber in both trials of 2019 and 2020.

Treatment	2019				2020			
	Trial I		Trial II		Trial I		Trial II	
	Flowering	Fruit set	Flowering	Fruit set	Flowering	Fruit set	Flowering	Fruit set
Variety								
CU 999	21.22	32.14	23.25	34.17	29.25	40.17	31.25	42.17
Monalisa	26.67	37.81	28.69	39.83	29.89	41.03	31.89	43.03
LSD	0.727	1.153	0.727	1.153	ns	ns	ns	ns
Spacing								
75 × 25 cm	25.29	36.38	27.33	38.42	29.95	40.83	31.75	42.83
75 × 50 cm	23.75	34.83	25.75	36.83	29.38	40.46	31.38	42.46
75 × 75 cm	22.79	33.71	24.83	35.75	29.58	40.50	31.58	42.50
LSD	1.107	0.995	1.160	1.066	ns	ns	ns	ns
NPK rate (kg ha⁻¹)								
0	25.83	37.61	27.89	39.67	30.94	42.72	32.94	44.72
100	24.61	35.89	26.61	37.89	29.89	41.17	31.89	43.17
200	23.28	34.06	25.33	36.11	29.39	40.17	31.39	42.17
300	22.06	32.33	24.06	34.33	28.06	38.33	30.06	40.33
LSD	0.390	0.487	0.385	0.482	0.823	0.887	0.823	0.887

ns = not significant. LSD ($P \leq 0.05$)**Table 4.** Effect of variety, spacing and NPK fertiliser rate on fruit girth (mm), fruit length (cm) and unit fruit weight (kg) of cucumber in both trials of 2019 and 2020.

Treatment	2019						2020					
	Trial I			Trial II			Trial I			Trial II		
	Girth	Length	Weight	Girth	Length	Weight	Girth	Length	Weight	Girth	Length	Weight
Variety												
CU 999	55.65	23.90	359.00	57.21	24.24	367.00	52.76	20.37	279.00	39.13	12.84	144.00
Monalisa	46.28	18.04	111.00	50.59	20.81	142.00	43.54	15.50	180.00	31.82	11.31	84.00
LSD	1.652	2.906	171.50	3.173	1.452	34.60	1.800	2.279	ns	ns	ns	50.20
Spacing												
75 × 25 cm	51.44	20.66	276.00	49.29	21.29	324.00	42.82	15.97	158.00	33.44	11.41	146.00
75 × 50 cm	50.98	21.13	258.00	57.12	23.63	262.00	51.27	18.76	250.00	37.18	12.30	113.00
75 × 75 cm	50.47	21.13	169.00	55.30	22.61	178.00	50.36	19.08	289.00	35.80	12.67	83.00
LSD	ns	ns	ns	0.604	0.319	20.60	3.273	1.115	82.70	ns	ns	43.8.
NPK rate (kg ha⁻¹)												
0	50.93	20.02	218.00	45.91	18.72	150.00	44.57	16.54	172.00	32.08	11.32	87.00
100	50.57	20.85	224.00	56.41	23.11	261.00	48.03	17.94	203.00	36.11	11.50	103.00
200	50.56	20.96	240.00	58.82	23.91	214.00	48.71	18.40	253.00	35.30	12.87	127.00
300	51.79	22.07	258.00	54.47	24.35	392.00	51.13	18.86	289.00	38.41	12.59	139.00
LSD	ns	1.063	ns	3.248	1.377	22.00	3.264	1.487	58.20	3.487	1.293	29.60

ns = not significant. LSD ($P \leq 0.05$)

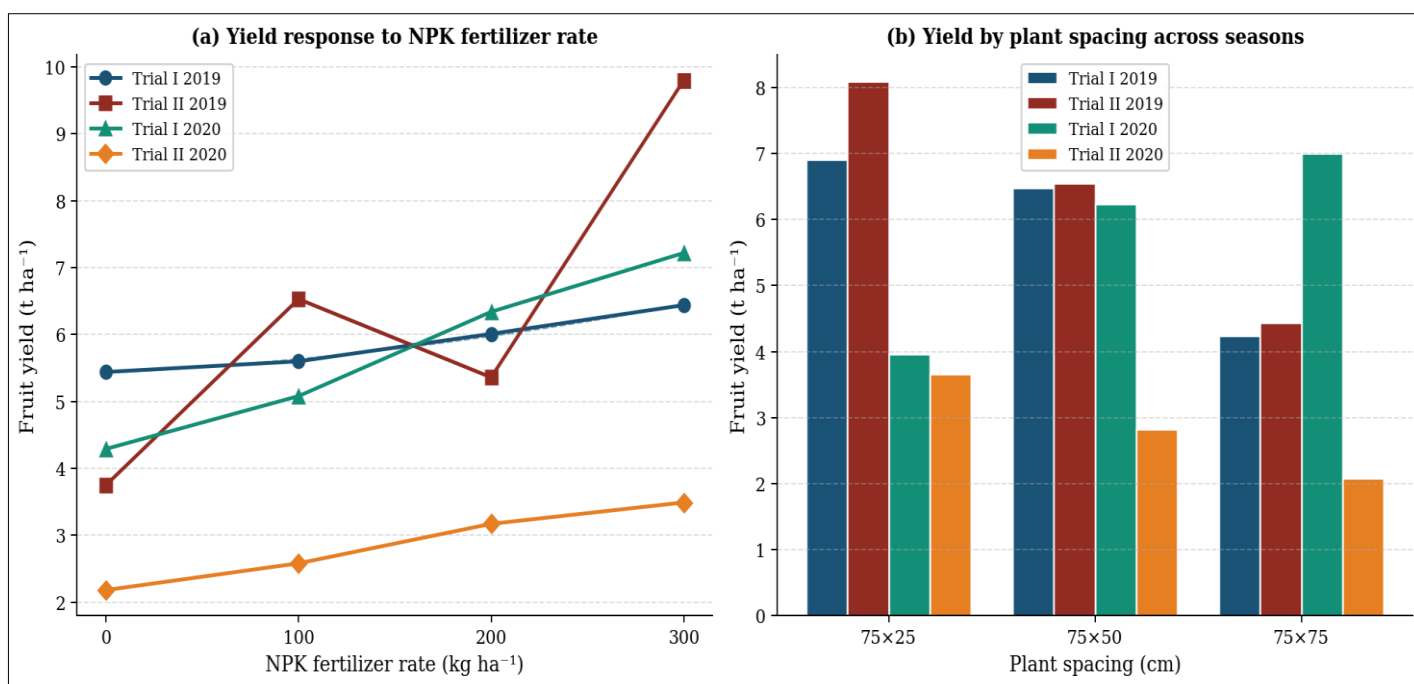


Figure 1. Fruit yield (t ha⁻¹) of cucumber (*Cucumis sativus* L.) in response to (a) NPK fertiliser rate across four trials (2019–2020) with polynomial regression line for Trial I 2019; (b) plant spacing across all four trials. All means represent treatment averages across varieties.

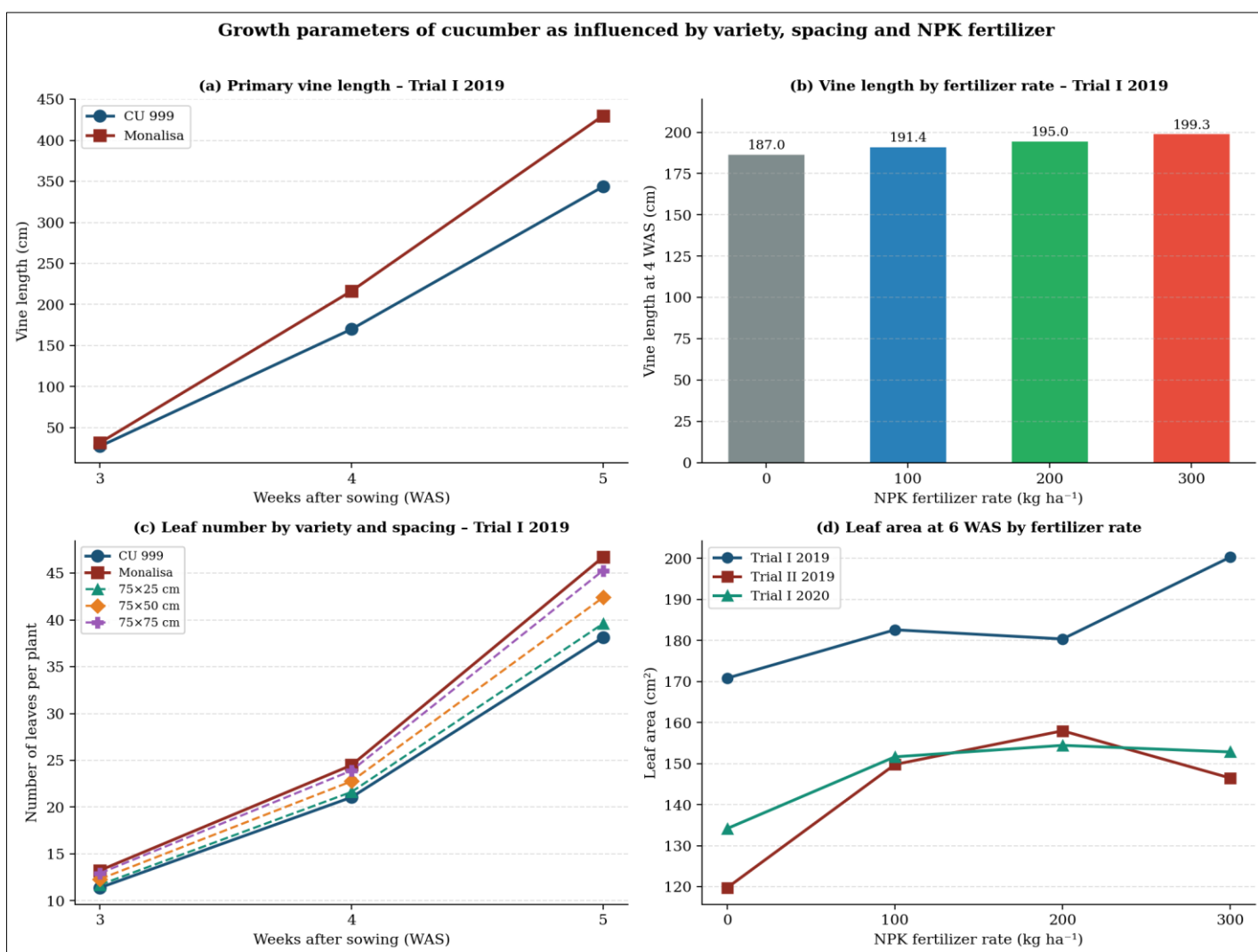


Figure 2. Growth parameters of cucumber (*Cucumis sativus* L.) as influenced by variety, spacing and NPK fertiliser rate: (a) primary vine length by variety at 3–5 WAS in Trial I 2019; (b) vine length at 4 WAS by NPK rate in Trial I 2019; (c) leaf number per plant by variety and spacing at 3–5 WAS in Trial I 2019; (d) leaf area (cm²) at 6 WAS by NPK rate across three trials.

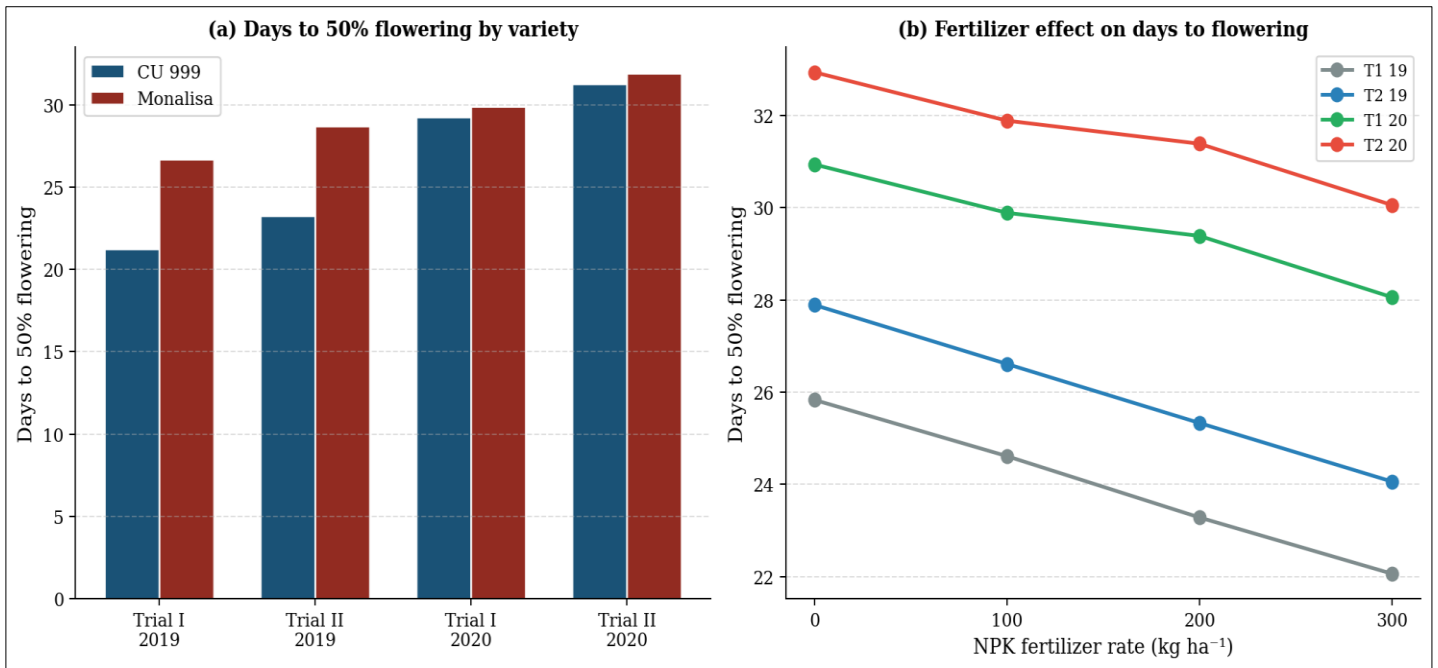


Figure 3. Days to 50% flowering of cucumber as influenced by (a) variety across four trials and (b) NPK fertiliser rate across all trials (2019–2020). Bars represent varietal means; lines represent fertiliser dose-response across trials.

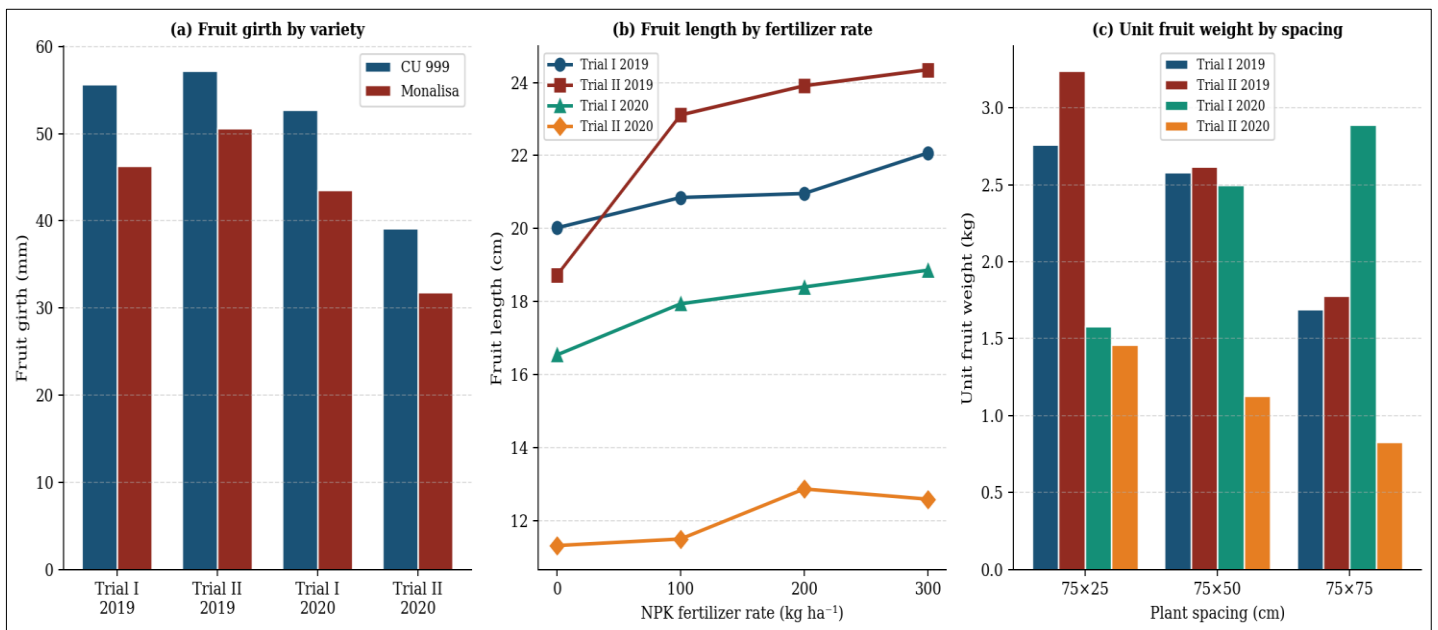


Figure 4. Fruit morphological parameters of cucumber: (a) fruit girth (mm) by variety across four trials; (b) fruit length (cm) by NPK fertiliser rate; (c) unit fruit weight (g) by plant spacing. Data represent treatment means; error bars not shown for clarity.

Days to 50% flowering and fruit set

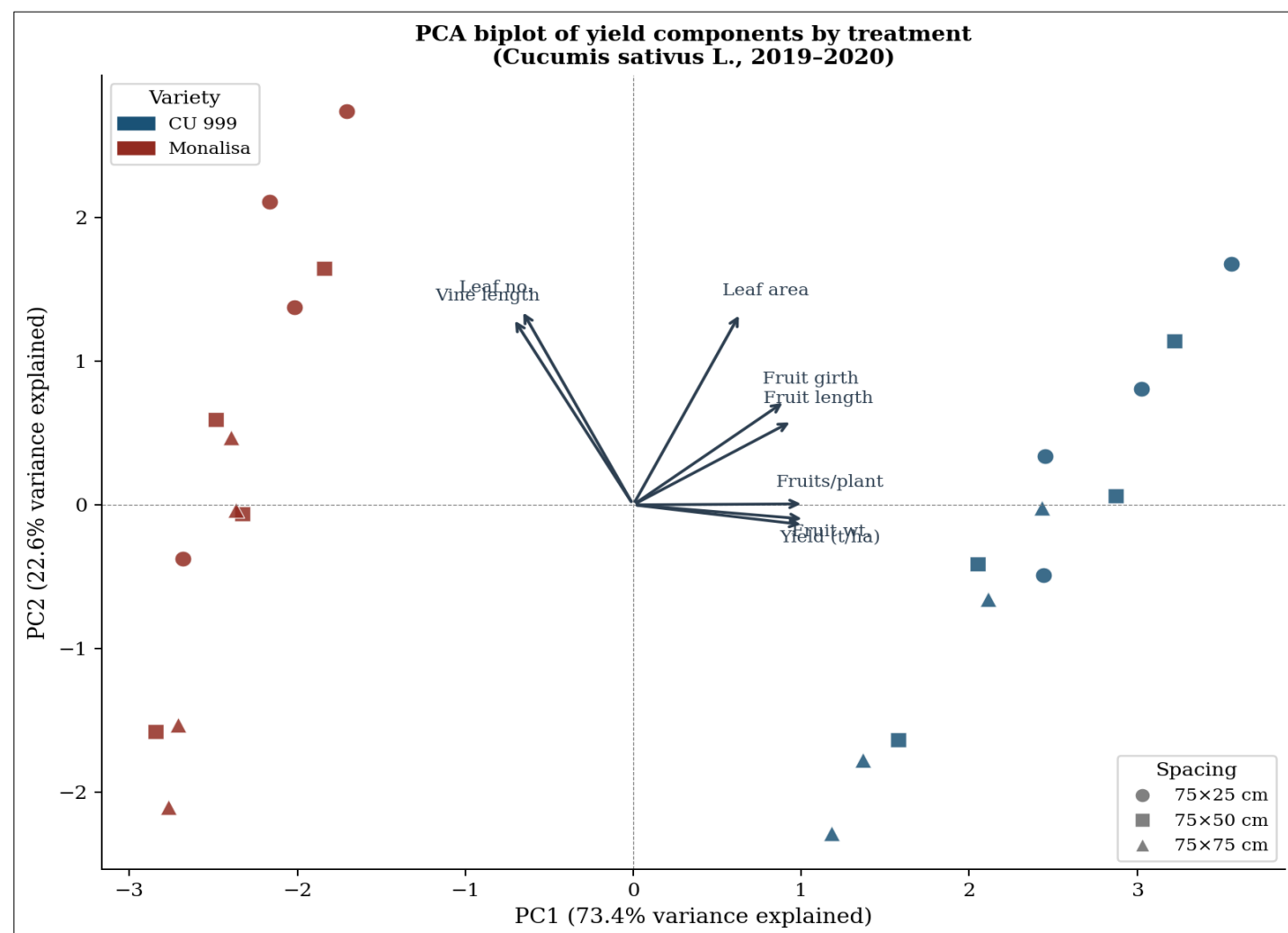
CU 999 flowered significantly earlier than Monalisa in both trials of 2019 (21.2 vs. 26.7 days in Trial I; LSD = 0.73; **Table 3; Figure 3a**). Plants at 75×75 cm spacing flowered 2.5 days earlier than those at 75×25 cm in Trial I of 2019 (22.8 vs. 25.3 days; LSD = 1.11). NPK at 300 kg ha⁻¹ consistently reduced days to 50% flowering across all four trials by 3.8 days in Trial I and 3.8 days in Trial II of 2019, and by 2.9 and 2.9 days in Trials I and II of 2020 respectively (LSD = 0.39–0.82; **Figure 3b**). The same treatment ranked first for earliest fruit set in every season (**Table 3**). Significant variety × spacing interactions in both 2019 trials confirmed that CU 999 × 75×75 cm achieved the earliest flowering in both seasons.

Fruit girth, length and unit weight

CU 999 produced fruits with significantly greater girth (55.7 vs. 46.3 mm; LSD = 1.65), longer fruits (23.9 vs. 18.0 cm; LSD = 2.91) and heavier individual fruits (359 vs. 111 g; LSD = 171.5) than Monalisa in Trial I of 2019 (**Table 4; Figure 4a**). These varietal advantages were reproduced in three of the remaining four trials. NPK at 300 kg ha⁻¹ significantly increased fruit length across all seasons (e.g., 22.1 vs. 20.0 cm at 300 vs. 0 kg ha⁻¹ in Trial I 2019; LSD = 1.06; **Figure 4b**). Narrower spacing (75×25 cm) generally produced heavier unit fruit weights in 2019 (324 g vs. 262 g vs. 178 g LSD = 20.6; Trial II), while wider spacing favoured fruit girth in some trials. Significant three-way interactions for fruit weight were observed in both 2019 trials; CU 999 × 75×25 cm × 300 kg ha⁻¹ yielded the highest unit weight (1,360 g fruit⁻¹) in Trial II.

Table 5. Effect of variety, spacing and NPK fertiliser rate on number of fruits per plant and fruit yield ($t\ ha^{-1}$) of cucumber in both trials of 2019 and 2020.

Treatment	2019				2020			
	Trial I		Trial II		Trial I		Trial II	
	Fruits/plant	Yield (t/ha)	Fruits/plant	Yield (t/ha)	Fruits/plant	Yield (t/ha)	Fruits/plant	Yield (t/ha)
Variety								
CU 999	9.17	8.97	11.11	9.18	9.72	6.97	7.25	3.60
Monalisa	4.92	2.78	6.10	3.54	8.03	4.49	5.33	2.10
LSD	3.422	4.288	0.195	0.865	1.644	ns	1.259	1.255
Spacing								
75 × 25 cm	8.73	6.91	10.84	8.09	6.62	3.96	7.21	3.66
75 × 50 cm	7.56	6.48	8.59	6.55	10.67	6.24	6.25	2.82
75 × 75 cm	4.83	4.24	6.38	4.44	9.34	7.00	5.42	2.08
LSD	2.595	ns	0.366	0.515	2.148	2.068	ns	1.095
NPK rate ($kg\ ha^{-1}$)								
0	6.47	5.44	5.10	3.75	7.06	4.29	4.47	2.18
100	6.97	5.60	8.71	6.53	8.61	5.08	5.44	2.58
200	6.89	6.01	7.31	5.36	9.23	6.34	6.44	3.17
300	7.83	6.44	13.30	9.80	10.61	7.22	8.50	3.49
LSD	ns	ns	0.655	0.550	2.209	1.456	1.783	0.741

ns = not significant. LSD ($P \leq 0.05$)Figure 5. Principal component analysis (PCA) biplot of eight yield-component variables across 24 treatment combinations (*Cucumis sativus* L., 2019–2020). Loading arrows represent each variable; symbols are treatment scores coded by variety (colour) and plant spacing (shape). Ellipses indicate 90% confidence regions per variety.

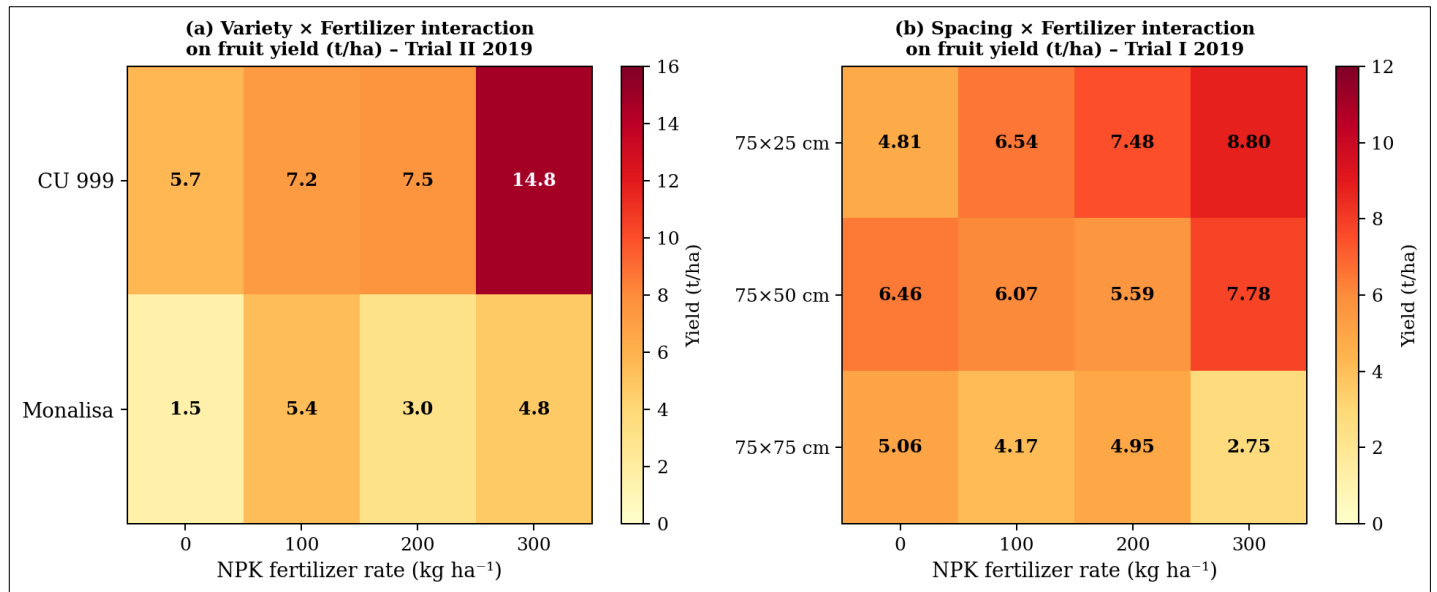


Figure 6. Interaction heatmaps showing mean fruit yield (t ha⁻¹): (a) Variety × NPK fertiliser rate in Trial II 2019; (b) Plant spacing × NPK fertiliser rate in Trial I 2019. Cell values are unadjusted treatment means.

Number of fruits per plant

CU 999 had significantly more fruits per plant than Monalisa in all trials (9.17 vs. 4.92 in Trial I 2019; LSD = 3.42; **Table 5**). The 75×25 cm spacing produced the most fruits per plant in both 2019 trials (8.73 and 10.84), while in Trial I of 2020 wider spacings (75×50 and 75×75 cm) were superior, possibly reflecting differences in canopy microclimate at higher humidity. Fertiliser at 300 kg ha⁻¹ significantly increased fruit numbers in Trial II of 2019 (13.30 vs. 5.10 at control; LSD = 0.66) and both trials of 2020.

Fruit yield

CU 999 consistently outyielded Monalisa: 8.97 vs. 2.78 t ha⁻¹ in Trial I 2019 (LSD = 4.29) and 9.18 vs. 3.54 t ha⁻¹ in Trial II 2019 (LSD = 0.87; **Table 5**; **Figure 1**). Plants at 75×25 cm spacing produced the highest yield in three of four trials (8.09 t ha⁻¹ in Trial II 2019; **Figure 1b**). NPK at 300 kg ha⁻¹ produced the highest yields in Trial II of 2019 (9.80 t ha⁻¹) and in both trials of 2020, with yield increasing in a near-linear fashion with NPK rate in the 2019 data (**Figure 1a**). A significant three-way interaction was recorded in both 2019 trials; in Trial I of 2019, the Spacing × Fertiliser interaction revealed 75×25 cm × 300 kg ha⁻¹ as the highest-yielding combination (8.80 t ha⁻¹; **Table 5**, **Figure 6**). In Trial II of 2019, CU 999 × 75×25 cm × 300 kg ha⁻¹ was the overall highest-performing combination.

Principal component analysis of yield components

PCA of the eight yield-component variables revealed that PC1 (loading primarily onto yield, fruits per plant and unit fruit weight) and PC2 (vine length, leaf number) together explained the dominant axes of treatment variation (**Figure 5**). CU 999 treatments clustered in the positive PC1 region, confirming the variety's overarching harvest advantage. Treatments receiving 300 kg ha⁻¹ NPK were consistently displaced toward higher PC1 and PC2 scores, reflecting simultaneous enhancement of vegetative vigour and reproductive output. The partial orthogonality of vine length and leaf area loading vectors

relative to yield vectors visualises the vegetative-reproductive trade-off that underpins the spacing effect: wider spacing promotes vegetative biomass (high PC2) without necessarily increasing per-hectare yield (lower PC1 at 75×75 cm). Significant positive co-directionality between the yield and unit fruit weight vectors confirms that the variety-spacing-fertiliser combination optimal for high yield was also optimal for large individual fruit size.

Discussion

The consistently superior yield and fruit morphological attributes of variety CU 999 over Monalisa across multiple trials broadly support findings by Ehiokhilen & Remison (2010) and Falaiye et al. (2022), who documented significant genotypic variation in cucumber performance under Nigerian field conditions. CU 999's genetic constitution evidently confers greater fruit sink strength and more efficient assimilate partitioning toward reproductive tissues, as reflected by its larger girth, longer fruits, heavier unit weights and higher fruits per plant. Importantly, Monalisa's longer vines and greater leaf counts in Trial I of 2019 did not translate into commensurate yield advantage a pattern consistent with the concept of source-sink imbalance in high-biomass cucurbit genotypes documented by Lawal (2000) and further reported for cucumbers in Cameroon by Chotangui et al. (2022). That study, comparing two varieties of cucumber across organic and inorganic fertiliser treatments in the western highlands of Cameroon an environment broadly comparable to SW Nigeria found that varietal identity was the strongest predictor of yield variation, with the higher-yielding variety outperforming regardless of fertiliser source, echoing the primacy of variety selection observed here.

The yield advantage of the 75×25 cm spacing in three of four trials aligns with the foundational work of Wanna (1993), Nerson (1998) and Nweke et al. (2013) and is corroborated by the recent study of Ding et al. (2022). Ding et al. (2022) conducted a multi-period greenhouse study at three plant densities (2.25, 3.0, 3.75 plants m⁻²) and found that, while lower density improved per-plant performance, total area yield was not significantly reduced a finding consistent with the

principle that closer spacing under open-field tropical conditions compensates individual plant suppression through greater population size. The reversal of the spacing effect observed in Trial I of 2020, where 75×75 cm outperformed 75×25 cm, is likely attributable to the lower rainfall in 2020 (1,017 mm vs. 1,413 mm in 2019): under drier conditions, lower plant density may reduce soil moisture competition, as suggested by Fasina et al. (2021) in their investigation of irrigation frequency effects on cucumber yield efficiency in southwestern Nigeria. This environment-dependent response to plant density reinforces that spacing recommendations must account for seasonal rainfall distribution, a finding with direct practical relevance for smallholder farmers managing irrigated and rainfed cucumber plots in SW Nigeria.

The positive, consistent response of all growth and yield parameters to increasing NPK rates culminating in peak performance at 300 kg ha⁻¹ confirms the fertility responsiveness of cucumber on the low-organic-matter soils of the study site. These results are broadly consistent with those of Bello et al. (2023), who demonstrated in a split-plot field study in Qatar that cucumber yield increased linearly with nitrogen rate up to the full recommended dose (100 kg N ha⁻¹ as urea), with sub-optimal N levels reducing both vegetative growth and fruit number regardless of irrigation regime. Acharya et al. (2024), working in the humid sub-tropics of Nepal, similarly found that the combination of FYM + NPK produced the highest cucumber growth and yield under both mulched and unmulched conditions, attributing this response to sustained nutrient availability and improved soil physical properties. Although the present study used mineral NPK alone, the magnitude of the yield response to 300 kg ha⁻¹ (up to 9.80 t ha⁻¹ vs. 3.75 t ha⁻¹ at 0 kg ha⁻¹ in Trial II 2019) approximately 2.6-fold is within the range reported by these authors and underscores the urgency of targeted fertiliser recommendations for Nigerian smallholder cucumber systems where NPK application rates are often inadequate or absent entirely (Eleduma, 2023).

The early-flowering and early-fruitletting response to 300 kg ha⁻¹ NPK (3.8–6.4 days reduction in days to 50% flowering) has important commercial implications. Earliness confers access to premium early-season markets and extends the potential harvesting window, possibly enabling a second ratoon crop within the same season. This finding is consistent with the work of Ahmed et al. (2007), who attributed accelerated phenological development in fertilised cucumber to enhanced nitrogen-mediated chlorophyll synthesis, increased leaf area and accelerated rate of assimilate production that collectively advance the vegetative-to-reproductive transition. More recently, Arif et al. (2023) documented that NPK applied at 100:50:50 kg ha⁻¹ in combination with biochar at 2 t ha⁻¹ produced the highest vine length, fruits per plant and yield in cucumber compared with controls, with the fertilised plants consistently entering reproductive stages earlier an observation that reinforces the mechanistic role of macronutrient availability in shortening the crop cycle.

The significance of the three-way interaction (Variety × Spacing × Fertiliser) for fruit yield in two of four trials underscores that the agronomic optimum for any one factor is conditioned by the levels of the other two. This interaction rarely reported in a single cucumber study with a full factorial design across multiple environments implies that blanket fertiliser recommendations without consideration of variety and spacing choice are likely to be suboptimal. Adekiya et al. (2022), in a soilless-media evaluation of fertiliser effects on

cucumber and tomato production, noted that the quality of crop response to fertiliser was strongly modulated by environmental context, cautioning against universal extension recommendations. The PCA results further illustrate this multi-dimensionality: no single factor independently explains the variation in yield components; rather, the synergistic combination of CU 999 (high-yielding genotype) × 75×25 cm (high population density) × 300 kg ha⁻¹ NPK (maximal fertility) drives performance in the positive PC1 direction simultaneously maximising yield, fruit number and fruit weight. This multi-criteria optimisation perspective is consistent with the integrated production approach advocated for vegetable intensification under smallholder tropical conditions (Acharya et al., 2024; Eleduma, 2023).

The seasonal variability observed between 2019 and 2020 particularly in vine length and the direction of the spacing effect highlights the importance of multi-season evaluation in tropical agronomy. Single-season studies are vulnerable to confounding by annual weather variation, as demonstrated by the contrasting rainfall totals and distributions between the two years. The four-trial design of the present study confers greater confidence in the robustness of the primary recommendation (CU 999 × 75×25 cm × 300 kg ha⁻¹) than would any single-season result alone. This multi-environment approach is aligned with the call by Gruda et al. (2017) for experimental designs that account for climate variability in developing practical production guidelines for vegetable crops in the tropics.

Conclusions

This four-trial, two-year study across the forest-savanna transition zone of SW Nigeria demonstrates that the simultaneous optimisation of variety, plant density and NPK fertiliser rate is essential for maximising cucumber productivity. Variety CU 999 consistently outperformed Monalisa across growth, phenological and yield parameters. Closer spacing (75×25 cm; 53,333 plants ha⁻¹) maximised per-hectare fruit yield in most environments. NPK 15-15-15 at 300 kg ha⁻¹ advanced flowering and fruit set, and increased fruit yield in all trials where the fertiliser effect was statistically significant. The treatment combination CU 999 × 75×25 cm × 300 kg ha⁻¹ NPK is recommended for high-yield cucumber production under similar agro-ecological conditions. Findings are corroborated by recent multi-environment studies from Nigeria, Cameroon, Nepal and Qatar, confirming the global relevance of balanced fertilisation and genotype selection in cucurbit production systems. Future research should prioritize (i) economic analysis of the 300 kg NPK ha⁻¹ rate to determine the economic optimum for smallholder farmers, and (ii) evaluation of organic–inorganic fertiliser combinations at this optimum NPK rate to promote sustainable intensification under tropical conditions.

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