



## Research article

# Effects of Plant Spacing and Starflow-CMZ Foliar Fertilizer Rates on the Growth, Yield, and Yield Components of Maize (*Zea mays* L.) Hybrids

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## ABSTRACT

A field experiment was conducted to evaluate the individual and interactive effects of plant spacing, Starflow-CMZ foliar fertilizer rate, and hybrid selection on the vegetative growth and grain yield of maize (*Zea mays* L.). Three plant spacings (15, 18, and 21 cm), three Starflow-CMZ rates (0-, 1-, and 2-mL L<sup>-1</sup>), and three hybrids (OSSK 515, KORDUNA MR, and ZP 6263) were arranged in a factorial design, and plant height, flag leaf area, chlorophyll content (SPAD), ear length, rows per ear, kernels per ear, 100-kernel weight, harvest index, and total grain yield were recorded. All three factors were found to significantly affect every trait measured, whereas significant interactions among them were detected only for chlorophyll reading, kernel number per ear, 100-kernel weight, harvest index, and total grain yield. Total grain yield was increased by about 37 percent when spacing was widened from 15 to 21 cm, an improvement that was attributed mainly to a greater number of kernels and heavier kernels. Chlorophyll content was raised by nearly 31 percent as the Starflow-CMZ rate was increased; however, the highest grain yield was obtained at the intermediate rate of 1 mL per liter rather than at the maximum rate tested, a pattern that was linked to a spacing-dependent response, since yield continued to rise with fertilizer rate at narrow spacing but was already maximized without fertilizer at the widest spacing. Among the hybrids, ZP 6263 was found to outyield OSSK 515 by nearly 21 percent, and it was regarded as the most responsive hybrid overall. It is concluded that maize productivity can be optimized by growing the hybrid ZP 6263 at 21 cm plant spacing, while the intermediate Starflow-CMZ rate is recommended as a general application, particularly under conditions of higher inter-plant competition.

## 1. Introduction

Maize (*Zea mays* L.) is widely regarded as one of the most strategically important cereal crops worldwide, often described as the “queen of cereals” owing to its exceptional yield potential, efficient C4 photosynthetic pathway, and broad utility in human nutrition, livestock feed, and industry (Abo El-Ezz & Hafeez, 2019; Kathirvelan et al., 2025; Mut et al., 2022). A doubling of agricultural production by 2050 is projected to be required in order to meet the nutritional and energy demands of a rapidly growing global population (Mut et al., 2022), a target that depends heavily on optimized agronomic management and the deployment of high-yielding hybrids adapted to specific climatic and spatial

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conditions (Djalovic et al., 2024) . Among the management practices available to growers, canopy architecture, resource-use efficiency, and final crop yield are shaped most strongly by plant spacing and balanced micronutrient nutrition (Djalovic et al., 2024; Uddin, 2020).

Plant spacing is a fundamental agronomic variable because planting density, population structure, and the spatial distribution of the crop canopy are directly governed by it (Gaire et al., 2020; Uddin, 2020). How efficiently essential growth resources such as solar radiation, water, and soil nutrients are captured by a crop is, in turn, determined by planting geometry (Uddin, 2020). Leaf area index (LAI) and total above-ground biomass per unit area are maximized by narrow spacing (e.g., 15 cm) (Gaire et al., 2020), but inter-plant competition and mutual shading can be intensified by excessively high planting densities, whereby individual plant development is suppressed and key yield components such as ear length, ear diameter, and kernel number per row are reduced. Conversely, resource competition is alleviated by wider spacing (e.g., 21 cm), so that greater vegetative growth is achieved by individual plants and larger ears with heavier kernels are produced (Gaire et al., 2020).

Alongside plant density, high yields and grain quality are sustained largely through balanced crop nutrition, and particularly micronutrient management (Djalovic et al., 2024). Conventional soil-applied fertilizers are prone to slow nutrient release, leaching, volatilization, surface run-off, erosion, and chemical fixation (Asare et al., 2023) , constraints by which nutrient availability can be severely limited during the vegetative stages (V4 to VT), when maize nutrient demand is greatest. These soil-related limitations are circumvented by foliar fertilization, through which micronutrients are delivered directly to the leaf surface, where immediate incorporation into plant metabolic pathways is allowed by rapid absorption through the stomata and cuticle (Asare et al., 2023). Trace elements such as zinc (Zn), manganese (Mn), and copper (Cu) are indispensable for normal maize metabolism, growth, and cellular development (Brodowska et al., 2022). A central role in carbohydrate metabolism, cell division, chlorophyll biosynthesis, and the activation of enzymes such as carbonic anhydrase is played by zinc (Ashenafi et al., 2023; Crista et al., 2024; Kathirvelan et al., 2025) ; when it is deficient, internode elongation is restricted and chlorosis and necrosis of the leaves are induced ; Essential cofactor functions in the photosynthetic electron-transport chain, cellular respiration, cell-wall lignification, and protein synthesis are performed by manganese and copper (Crista et al., 2024) . Although leaf chlorophyll content (SPAD), ear yield, and grain quality can be improved by foliar application of Zn, Mn, and Cu, nutrient antagonism may be induced by inappropriate combinations or application rates (JARECKI et al., n.d.) . The optimal rate of foliar micronutrient application must therefore be identified so that crop performance is maximized while toxicity or metabolic imbalance is avoided (Crista et al., 2024).

Although the individual effects of planting geometry and micronutrient nutrition on maize performance have each been investigated, the interactive dynamics between narrow within-row spacing and combined Zn-Mn-Cu foliar fertilization remain insufficiently characterized. The present study was therefore undertaken so that the independent and interactive effects of three plant spacing levels (15, 18, and 21 cm) and three foliar application rates of Starflow-CMZ fertilizer (24.5% Zn, 24.5% Mn, and 9.5% Cu, applied at 0, 1, and 2 mL L<sup>-1</sup>) on the growth, yield, and yield components of three maize hybrids could be evaluated.

## **2. Materials and Methods**

### **2.1 Experimental site and design**

The field experiment was conducted in the Hammam Al-Alil district, Nineveh Governorate, Iraq (36.1801258° N, 43.2441619° E; approximately 215 m above sea level), a semi-arid zone classified as a semi-guaranteed rainfall area. Sowing was carried out in the first week of July 2025, during the 2025 spring growing season, and the crop was harvested in November 2025. The land was prepared by moldboard ploughing followed by harrowing to obtain a fine seedbed, after which ridges spaced 75 cm apart were formed. Diammonium phosphate (DAP) was applied at 200 kg ha<sup>-1</sup> at sowing, while urea was applied at 200 kg ha<sup>-1</sup> in two equal split applications, the first 21 days after sowing and the second immediately before tassel emergence. Irrigation was supplied by drip irrigation according to crop water requirements throughout the growing season. Soil physicochemical properties and the monthly temperature and relative humidity recorded over the growing season are presented in Tables 1 and 2, respectively.

A split-split-plot design with three replications was used. The main-plot factor was constituted by plant spacing, at three levels: 15 cm (88,889 plants ha<sup>-1</sup>), 18 cm (74,074 plants ha<sup>-1</sup>), and 21 cm (63,492 plants ha<sup>-1</sup>). The sub-plot factor was constituted by foliar application of Starflow-CMZ, at three concentrations (0, 1, and 2 mL per 100 L water), and the sub-sub-plot factor was constituted by maize hybrid, with three hybrids: OSSK 515, KORDUNA MR, and ZP 6263. Each experimental unit (sub-sub-plot) was sized at 3 × 3 m, corresponding to an area of 9 m<sup>2</sup>. Starflow-CMZ is a commercial suspension-concentrate fertilizer manufactured by Fertiplus (France), containing 24.5% zinc, 24.5% manganese, and 9.5% copper. The foliar spray was applied at the onset of tassel emergence using a calibrated sprayer to ensure uniform leaf coverage, while an equivalent volume of water only was received by control plots. Uniformity was maintained for all other agronomic practices across the experimental units.

## 2.2 Traits recorded

### 2.2.1. Vegetative growth traits

*Plant height* (cm): measured from the soil surface to the tip of the tassel.

*Flag leaf area* (cm<sup>2</sup>): estimated for the leaf subtending the ear using the formula Leaf Area = L × W × 0.75 (Mario et al., 2018), where L is leaf length, W is maximum leaf width, and 0.75 is the correction factor for maize leaves. *Chlorophyll index (SPAD)*: measured on the flag leaf using a portable chlorophyll meter, averaged across three readings per plant.

### 2.2.2. Yield components

*Ear length* (cm): measured from the base to the tip of the ear.

*Rows per ear*: counted manually on each sampled ear.

*Kernels per row*: counted manually; kernel number per ear was subsequently calculated as the product of rows per ear and kernels per row. *Kernels per ear*: determined directly using a seed counter after shelling. *100-kernel weight* (g): determined from a random sample of sound kernels after drying to constant weight.

### 2.2.3. Harvest index and total grain yield

*Harvest index* (%): calculated as HI (%) = (Grain yield / Biological yield) × 100 (Ludemann et al., 2022)

. *Total grain yield* (t ha<sup>-1</sup>): calculated from plot grain yield on the basis of the harvested area.

## 2.3. Statistical analysis

Data were subjected to analysis of variance appropriate to the split-split-plot design using GenStat statistical software (22nd Edition; VSN International, Hemel Hempstead, UK) (Baird et al., 2023). Plant spacing was tested against the main-plot error term, Starflow-CMZ concentration against

the sub-plot error term, and maize hybrid against the residual error term. Treatment means were separated using Fisher's protected least significant difference (LSD) test at the 5% probability level, and effects were declared significant at  $P \leq 0.05$  unless stated otherwise.

**Table 1. Physicochemical properties of the experimental soil (0–30 cm depth).**

| Soil property                                      | Value     |
|----------------------------------------------------|-----------|
| Sand (%)                                           | 39.55     |
| Clay (%)                                           | 27.95     |
| Silt (%)                                           | 32.50     |
| Total nitrogen (%)                                 | 0.0039    |
| Available phosphorus (ppm)                         | 4.32      |
| Available potassium (ppm)                          | 120       |
| Organic matter (%)                                 | 1.17      |
| pH                                                 | 8.07      |
| Electrical conductivity, EC ( $\text{dS m}^{-1}$ ) | 1.10      |
| Soil texture                                       | Clay loam |

**Table 2. Monthly mean air temperature and relative humidity at the experimental site (June–December 2025).**

| Month | Temperature ( $^{\circ}\text{C}$ ) | Relative humidity (%) |
|-------|------------------------------------|-----------------------|
| Jun.  | 32                                 | 21                    |
| Jul.  | 38                                 | 17                    |
| Aug.  | 37                                 | 19                    |
| Sep.  | 28                                 | 23                    |
| Oct.  | 24                                 | 36                    |
| Nov.  | 16                                 | 53                    |
| Dec.  | 10                                 | 78                    |

### 3. Results and Discussion

#### 3.1. Vegetative growth traits

##### 3.1.1. Analysis of variance and main effects

It was shown by analysis of variance (Table 3) that plant height ( $P = 0.047$ ), flag leaf area ( $P = 0.036$ ), and SPAD reading ( $P < 0.001$ ) were significantly affected by plant spacing. Plant height ( $P = 0.044$ ) and SPAD reading ( $P < 0.001$ ) were also significantly affected by the Starflow-CMZ rate, but statistical significance was not reached by its main effect on flag leaf area ( $P = 0.105$ ), even though flag leaf area was numerically increased with increasing Starflow-CMZ rate (Table 4). All three vegetative traits were significantly affected by hybrid ( $P < 0.001$  in every case). For all three factors, the same general direction was followed by mean values: an increase from the narrowest to the widest spacing (15 to 21 cm), from the lowest to the highest Starflow-CMZ rate (S0 to S2), and from OSSK 515/KORDUNA MR to ZP 6263 (Table 4).

**Table 3. Analysis of variance (significance levels) for vegetative growth traits.**

| Source of variation             | d.f. | Plant Height | Flag Leaf Area | SPAD |
|---------------------------------|------|--------------|----------------|------|
| Plant spacing (Distance)        | 2    | *            | *              | ***  |
| Starflow-CMZ (Starflow)         | 2    | *            | ns             | ***  |
| Spacing × Starflow-CMZ          | 4    | ns           | ns             | *    |
| Hybrid (Cultivars)              | 2    | ***          | ***            | ***  |
| Spacing × Hybrid                | 4    | ns           | ns             | **   |
| Starflow-CMZ × Hybrid           | 4    | ns           | ns             | ***  |
| Spacing × Starflow-CMZ × Hybrid | 8    | ns           | ns             | **   |

\*, \*\*, \*\*\* significant at  $P \leq 0.05$ ,  $P \leq 0.01$ , and  $P \leq 0.001$ , respectively; ns, not significant ( $P > 0.05$ ). Full analysis-of-variance tables (sums of squares, mean squares, and variance ratios) generated by GenStat are available from the corresponding author on request.

**Table 4. Main effects of plant spacing, Starflow-CMZ rate, and hybrid on vegetative growth traits.**

| Factor / Level                          | Plant Height (cm) | Flag Leaf Area (cm <sup>2</sup> ) | SPAD Reading |
|-----------------------------------------|-------------------|-----------------------------------|--------------|
| <b>Plant spacing (cm)</b>               |                   |                                   |              |
| 15                                      | 221.37            | 489.97                            | 45.90        |
| 18                                      | 229.07            | 502.58                            | 47.39        |
| 21                                      | 242.04            | 533.12                            | 48.33        |
| LSD (0.05)                              | 15.225            | 29.684                            | 0.0965       |
| <b>Starflow-CMZ (mL L<sup>-1</sup>)</b> |                   |                                   |              |
| S0 (0)                                  | 221.74            | 496.10                            | 40.48        |
| S1 (1)                                  | 232.48            | 510.91                            | 48.15        |
| S2 (2)                                  | 238.26            | 518.66                            | 52.98        |
| LSD (0.05)                              | 12.767            | 21.375                            | 0.071        |
| <b>Hybrid</b>                           |                   |                                   |              |
| OSSK 515                                | 227.96            | 496.48                            | 46.34        |
| KORDUNA MR                              | 227.07            | 506.89                            | 46.80        |
| ZP 6263                                 | 237.44            | 522.30                            | 48.48        |
| LSD (0.05)                              | 2.235             | 1.934                             | 0.0806       |

### 3.1.2. Two-way interactions

As shown in Table 3, the spacing × Starflow-CMZ, spacing × hybrid, and Starflow-CMZ × hybrid interactions were not statistically significant for plant height or flag leaf area ( $P > 0.05$  in every case), but were significant for SPAD reading. The cell means for plant height and flag leaf area presented in Table 5 therefore reflect the additive combination of significant main effects rather than a genuine synergistic response, and formal mean separation among individual two-way combinations is not statistically warranted for these two traits; they are presented only to illustrate the overall numeric trend. SPAD reading, in contrast, showed a true interactive response for all three two-way combinations. Spacing × Starflow-CMZ: SPAD increased from 39.10 (15 cm × S0) to 54.11 (21 cm × S2); because the LSD for this interaction was very small (0.123), nearly every one of the nine combinations differed significantly from every other. Spacing × Hybrid: SPAD ranged from 45.10 to 49.58 (LSD = 0.1349), with essentially all pairwise differences among the nine combinations statistically significant. Starflow-CMZ × Hybrid: values ranged from 45.10 (S0 × OSSK 515) to 49.58 (S2 × ZP 6263) (LSD = 0.1349); the intermediate row of this interaction corresponds to the 1 mL L<sup>-1</sup> rate (S1) combined with OSSK 515, labelled accordingly in Table 5 to avoid ambiguity with the S0 row.

**Table 5. Two-way interactions of plant spacing × Starflow-CMZ, plant spacing × hybrid, and Starflow-CMZ × hybrid on vegetative growth traits.**

| Interaction                  | Plant Height (cm) <sup>a</sup> | Flag Leaf Area (cm <sup>2</sup> ) <sup>a</sup> | SPAD Reading |
|------------------------------|--------------------------------|------------------------------------------------|--------------|
| Plant spacing × Starflow-CMZ |                                |                                                |              |

|                               |                           |                           |               |
|-------------------------------|---------------------------|---------------------------|---------------|
| 15 cm × S0                    | 211.22                    | 474.05                    | 39.10         |
| 15 cm × S1                    | 223.00                    | 491.54                    | 46.84         |
| 15 cm × S2                    | 229.89                    | 504.30                    | 51.76         |
| 18 cm × S0                    | 220.33                    | 491.03                    | 40.70         |
| 18 cm × S1                    | 230.56                    | 505.84                    | 48.39         |
| 18 cm × S2                    | 236.33                    | 510.89                    | 53.07         |
| 21 cm × S0                    | 233.67                    | 523.20                    | 41.64         |
| 21 cm × S1                    | 243.89                    | 535.35                    | 49.22         |
| 21 cm × S2                    | 248.56                    | 540.80                    | 54.11         |
| <i>LSD (0.05)</i>             | <i>21.093<sup>a</sup></i> | <i>37.375<sup>a</sup></i> | <i>0.123</i>  |
| <b>Plant spacing × Hybrid</b> |                           |                           |               |
| 15 cm × OSSK 515              | 218.78                    | 477.80                    | 45.10         |
| 15 cm × KORDUNA MR            | 217.89                    | 488.30                    | 45.41         |
| 15 cm × ZP 6263               | 227.44                    | 503.80                    | 47.19         |
| 18 cm × OSSK 515              | 226.33                    | 490.70                    | 46.39         |
| 18 cm × KORDUNA MR            | 224.78                    | 500.95                    | 47.10         |
| 18 cm × ZP 6263               | 236.11                    | 516.10                    | 48.67         |
| 21 cm × OSSK 515              | 238.78                    | 520.94                    | 47.52         |
| 21 cm × KORDUNA MR            | 238.56                    | 531.42                    | 47.88         |
| 21 cm × ZP 6263               | 248.78                    | 547.00                    | 49.58         |
| <i>LSD (0.05)</i>             | <i>14.973<sup>a</sup></i> | <i>29.557<sup>a</sup></i> | <i>0.1349</i> |
| <b>Starflow-CMZ × Hybrid</b>  |                           |                           |               |
| S0 × OSSK 515                 | 218.78                    | 477.80                    | 45.10         |
| S0 × KORDUNA MR               | 217.89                    | 488.30                    | 45.41         |
| S0 × ZP 6263                  | 227.44                    | 503.80                    | 47.19         |
| S1 × OSSK 515                 | 226.33                    | 490.70                    | 46.39         |
| S1 × KORDUNA MR               | 224.78                    | 500.95                    | 47.10         |
| S1 × ZP 6263                  | 236.11                    | 516.10                    | 48.67         |
| S2 × OSSK 515                 | 238.78                    | 520.94                    | 47.52         |
| S2 × KORDUNA MR               | 238.56                    | 531.42                    | 47.88         |
| S2 × ZP 6263                  | 248.78                    | 547.00                    | 49.58         |
| <i>LSD (0.05)</i>             | <i>14.973<sup>a</sup></i> | <i>29.557<sup>a</sup></i> | <i>0.1349</i> |

<sup>a</sup> The corresponding ANOVA interaction term was not statistically significant ( $P > 0.05$ ; Table 3); LSD values are shown for descriptive completeness only and should not be used for pairwise significance testing of this trait.

### 3.1.3. Three-way interaction: plant spacing × Starflow-CMZ × hybrid

The three-way interaction was significant only for SPAD reading ( $P = 0.008$ ; Table 3); it was not significant for plant height ( $P = 1.000$ ) or flag leaf area ( $P = 1.000$ ). For SPAD, values ranged from 38.60 (15 cm, S0, OSSK 515) to 55.87 (21 cm, S2, ZP 6263); given the very small LSD (0.2271), essentially all 27 spacing × Starflow-CMZ × hybrid combinations differed significantly from one another, confirming a genuine and highly reproducible three-way interaction for this trait. The corresponding numeric ranges for plant height (208.33–255.67 cm) and flag leaf area (462.66–556.42 cm<sup>2</sup>), shown in Table 6 for completeness, followed the same general direction but are not supported by a significant interaction term and should therefore be interpreted only as the additive outcome of the significant main effects described in Section 3.1.1. In every case, the combination of 21 cm spacing, 2 mL L<sup>-1</sup> Starflow-CMZ, and the hybrid ZP 6263 produced the highest values for all three traits, whereas 15 cm spacing with no Starflow-CMZ, combined with OSSK 515 or KORDUNA MR, produced the lowest.

There were however deeper nodes which had relatively lower bootstrap values (0.12–0.53) which indicated a lack of confidence in solving basal evolutionary relationships. Also, some internal branches were moderately supported (e.g., 0.2243–0.345), which is indicative of the absence of phylogenetic signal in some parts of the dataset. These smaller values can probably be explained by the conserved

nature of mitochondrial sequences and the relatively short sequence length being examined. They can also indicate rapid cases of evolutionary radiation where two or more lineages split over a short time period of evolution, making them less resolved at deeper nodes. They can also indicate rapid cases of evolutionary radiation where two or more lineages split over a short time period of evolution, making them less resolved at deeper nodes.

**Table 6. Three-way interaction of plant spacing, Starflow-CMZ rate, and hybrid on vegetative growth traits.**

| Spacing (cm)      | Starflow (mL L <sup>-1</sup> ) | Plant Height (cm) <sup>a</sup> |             |         | Flag Leaf Area (cm <sup>2</sup> ) <sup>a</sup> |            |         | SPAD Reading  |             |         |
|-------------------|--------------------------------|--------------------------------|-------------|---------|------------------------------------------------|------------|---------|---------------|-------------|---------|
|                   |                                | OSSK 515                       | KORDUN A MR | ZP 6263 | OSSK 515                                       | KORDUNA MR | ZP 6263 | OSSK 515      | KORDUN A MR | ZP 6263 |
| 15                | S0                             | 209.00                         | 208.33      | 216.33  | 462.66                                         | 473.25     | 486.26  | 38.60         | 38.90       | 39.80   |
|                   | S1                             | 220.33                         | 219.67      | 229.00  | 479.35                                         | 489.90     | 505.38  | 46.10         | 46.37       | 48.07   |
|                   | S2                             | 227.00                         | 225.67      | 237.00  | 491.40                                         | 501.75     | 519.76  | 50.60         | 50.97       | 53.70   |
| 18                | S0                             | 217.67                         | 217.00      | 226.33  | 479.98                                         | 490.05     | 503.06  | 39.80         | 40.60       | 41.70   |
|                   | S1                             | 227.67                         | 226.33      | 237.67  | 493.67                                         | 504.25     | 519.60  | 47.57         | 48.10       | 49.50   |
|                   | S2                             | 233.67                         | 231.00      | 244.33  | 498.45                                         | 508.56     | 525.66  | 51.80         | 52.60       | 54.80   |
| 21                | S0                             | 231.00                         | 230.33      | 239.67  | 511.63                                         | 522.49     | 535.50  | 41.20         | 41.37       | 42.37   |
|                   | S1                             | 240.33                         | 240.33      | 251.00  | 523.38                                         | 533.59     | 549.08  | 48.37         | 48.80       | 50.50   |
|                   | S2                             | 245.00                         | 245.00      | 255.67  | 527.82                                         | 538.18     | 556.42  | 53.00         | 53.47       | 55.87   |
| <b>LSD (0.05)</b> |                                | <b>21.624<sup>a</sup></b>      |             |         | <b>37.591<sup>a</sup></b>                      |            |         | <b>0.2271</b> |             |         |

<sup>a</sup> Three-way interaction not statistically significant ( $P > 0.05$ ; Table 3); means shown for descriptive purposes only.

### 3.1.4. Discussion of vegetative growth traits

The pattern revealed by the analysis of variance, in which SPAD reading responded interactively to spacing, Starflow-CMZ rate, and hybrid while plant height and flag leaf area responded largely additively, is agronomically coherent. SPAD reading is a rapid physiological indicator of leaf chlorophyll status that responds within days to changes in micronutrient supply and light availability, whereas plant height and flag leaf area are structural traits whose final expression is buffered by developmental compensation over the whole growing season. This distinction between rapidly responsive physiological traits and more conservative structural traits has been noted in maize agronomy: nitrogen or micronutrient inputs typically produce their most immediate and interaction-sensitive effects on leaf chlorophyll and photosynthetic indices, while structural traits tend to integrate the main effects of density and genotype more independently unless resource limitation becomes severe (Tian et al., 2022). The significant spacing  $\times$  Starflow-CMZ interaction for SPAD, with the largest chlorophyll gains from Starflow-CMZ occurring at the widest spacing (21 cm), agrees with reports that the physiological benefit of a foliar or fertilizer input depends strongly on the spacing under which it is applied, because reduced inter-plant competition allows each plant greater access to both the applied micronutrients and to incident light (Tian et al., 2022).

The consistent superiority of ZP 6263 in plant height, flag leaf area, and SPAD reading, evident as a significant main effect for all three traits, agrees with the general principle that maize hybrids differ in their inherent vegetative growth potential. Multi-environment maize hybrid trials have reported substantial genotypic variation for plant height, leaf-related traits, and physiological indices (Alam et al., 2022). That this

hybrid effect was significant on its own but did not translate into significant spacing  $\times$  hybrid or Starflow-CMZ  $\times$  hybrid interactions for plant height and flag leaf area suggests that ZP 6263's structural growth advantage was expressed consistently across all spacing and Starflow-CMZ treatments, rather than being conditional on a particular management combination; only its chlorophyll response (SPAD) was further modulated by spacing and Starflow-CMZ rate.

### 3.2. Yield components

#### 3.2.1. Analysis of variance and main effects

It was shown by analysis of variance (Table 7) that ear length ( $P = 0.035$ ), rows per ear ( $P = 0.018$ ), kernel number per ear ( $P < 0.001$ ), and 100-kernel weight ( $P < 0.001$ ) were significantly affected by plant spacing. Rows per ear ( $P = 0.026$ ), kernel number per ear ( $P < 0.001$ ), and 100-kernel weight ( $P < 0.001$ ) were also significantly affected by the Starflow-CMZ rate, but statistical significance was not reached by its main effect on ear length ( $P = 0.342$ ), although ear length was numerically increased with Starflow-CMZ rate (Table 8). All four yield components were significantly affected by hybrid ( $P < 0.001$  in every case).

**Table 7. Analysis of variance (significance levels) for yield components.**

| Source of variation                           | d.f. | Ear Length | Rows/Ear | Kernels/Ear | 100-Kernel Wt. |
|-----------------------------------------------|------|------------|----------|-------------|----------------|
| Plant spacing (Distance)                      | 2    | *          | *        | ***         | ***            |
| Starflow-CMZ (Starflow)                       | 2    | ns         | *        | ***         | ***            |
| Spacing $\times$ Starflow-CMZ                 | 4    | ns         | ns       | ***         | ***            |
| Hybrid (Cultivars)                            | 2    | ***        | ***      | ***         | ***            |
| Spacing $\times$ Hybrid                       | 4    | ns         | ns       | ***         | ***            |
| Starflow-CMZ $\times$ Hybrid                  | 4    | ns         | ns       | ***         | ***            |
| Spacing $\times$ Starflow-CMZ $\times$ Hybrid | 8    | ns         | ns       | ***         | ***            |

\*, \*\*, \*\*\* significant at  $P \leq 0.05$ ,  $P \leq 0.01$ , and  $P \leq 0.001$ , respectively; ns, not significant ( $P > 0.05$ ).

**Table 8. Main effects of plant spacing, Starflow-CMZ rate, and hybrid on yield components.**

| Factor / Level                          | Ear Length (cm) | Rows per Ear | Kernels per Ear | 100-Kernel Weight (g) |
|-----------------------------------------|-----------------|--------------|-----------------|-----------------------|
| <b>Plant spacing (cm)</b>               |                 |              |                 |                       |
| 15                                      | 17.51           | 13.84        | 454.00          | 29.74                 |
| 18                                      | 18.13           | 14.03        | 507.11          | 30.90                 |
| 21                                      | 19.77           | 14.41        | 570.33          | 32.18                 |
| <i>LSD (0.05)</i>                       | 1.5448          | 0.3194       | 0.2908          | 0.0697                |
| <b>Starflow-CMZ (mL L<sup>-1</sup>)</b> |                 |              |                 |                       |
| S0 (0)                                  | 17.93           | 13.80        | 448.33          | 28.97                 |
| S1 (1)                                  | 18.57           | 14.11        | 515.44          | 31.30                 |
| S2 (2)                                  | 18.91           | 14.36        | 567.67          | 32.55                 |
| <i>LSD (0.05)</i>                       | 1.4064          | 0.3856       | 0.2282          | 0.1125                |
| <b>Hybrid</b>                           |                 |              |                 |                       |
| OSSK 515                                | 17.69           | 13.79        | 479.78          | 30.14                 |
| KORDUNA MR                              | 18.36           | 14.02        | 502.56          | 30.79                 |
| ZP 6263                                 | 19.37           | 14.46        | 549.11          | 31.90                 |
| <i>LSD (0.05)</i>                       | 0.3191          | 0.0728       | 0.1062          | 0.0663                |

#### 3.2.2. Two-way interactions

According to Table 7, none of the two-way interactions (spacing  $\times$  Starflow-CMZ, spacing  $\times$  hybrid, or Starflow-CMZ  $\times$  hybrid) were statistically significant for ear length or rows per ear ( $P > 0.05$  in every

case); the corresponding cell means in Table 9 therefore represent the additive combination of significant main effects and are shown for descriptive purposes only. Kernel number per ear and 100-kernel weight, in contrast, showed highly significant two-way interactions at every level ( $P < 0.001$ ). Spacing  $\times$  Starflow-CMZ: kernel number per ear rose from 381.00 (15 cm  $\times$  S0) to 619.00 (21 cm  $\times$  S2); with a very small LSD (0.3858), virtually every one of the nine combinations differed significantly from every other. The 100-kernel weight rose from 27.48 g to 33.43 g (LSD = 0.1652), with almost all pairwise differences significant. Spacing  $\times$  Hybrid: kernel number per ear ranged from 424.33 (15 cm  $\times$  OSSK 515) to 609.00 (21 cm  $\times$  ZP 6263) (LSD = 0.2915), and 100-kernel weight ranged from 28.88 to 33.30 g (LSD = 0.107); in both cases nearly all combinations differed significantly. Starflow-CMZ  $\times$  Hybrid: kernel number per ear increased from 424.00 (S0  $\times$  OSSK 515) to 615.33 (S2  $\times$  ZP 6263) (LSD = 0.2643), and 100-kernel weight increased from 28.48 to 33.89 g (LSD = 0.1412); as with the vegetative traits, the intermediate row of this interaction corresponds to the 1 mL L<sup>-1</sup> rate (S1) combined with OSSK 515, labelled accordingly in Table 9.

**Table 9. Two-way interactions of plant spacing  $\times$  Starflow-CMZ, plant spacing  $\times$  hybrid, and Starflow-CMZ  $\times$  hybrid on yield components.**

| Interaction                                           | Ear Length<br>(cm) <sup>a</sup> | Rows per<br>Ear <sup>a</sup> | Kernels per<br>Ear | 100-Kernel Weight<br>(g) |
|-------------------------------------------------------|---------------------------------|------------------------------|--------------------|--------------------------|
| <b>Plant spacing <math>\times</math> Starflow-CMZ</b> |                                 |                              |                    |                          |
| 15 cm $\times$ S0                                     | 16.86                           | 13.57                        | 381.00             | 27.48                    |
| 15 cm $\times$ S1                                     | 17.57                           | 13.81                        | 457.00             | 30.20                    |
| 15 cm $\times$ S2                                     | 18.12                           | 14.13                        | 524.00             | 31.54                    |
| 18 cm $\times$ S0                                     | 17.69                           | 13.69                        | 444.67             | 28.84                    |
| 18 cm $\times$ S1                                     | 18.26                           | 14.09                        | 516.67             | 31.18                    |
| 18 cm $\times$ S2                                     | 18.46                           | 14.30                        | 560.00             | 32.68                    |
| 21 cm $\times$ S0                                     | 19.26                           | 14.16                        | 519.33             | 30.60                    |
| 21 cm $\times$ S1                                     | 19.90                           | 14.42                        | 572.67             | 32.51                    |
| 21 cm $\times$ S2                                     | 20.14                           | 14.66                        | 619.00             | 33.43                    |
| <b>LSD (0.05)</b>                                     | <b>2.2668<sup>a</sup></b>       | <b>0.5854<sup>a</sup></b>    | <b>0.3858</b>      | <b>0.1652</b>            |
| <b>Plant spacing <math>\times</math> Hybrid</b>       |                                 |                              |                    |                          |
| 15 cm $\times$ OSSK 515                               | 16.73                           | 13.56                        | 424.33             | 28.88                    |
| 15 cm $\times$ KORDUNA MR                             | 17.41                           | 13.78                        | 446.00             | 29.63                    |
| 15 cm $\times$ ZP 6263                                | 18.40                           | 14.18                        | 491.67             | 30.71                    |
| 18 cm $\times$ OSSK 515                               | 17.34                           | 13.70                        | 475.67             | 30.13                    |
| 18 cm $\times$ KORDUNA MR                             | 18.02                           | 13.94                        | 499.00             | 30.88                    |
| 18 cm $\times$ ZP 6263                                | 19.03                           | 14.43                        | 546.67             | 31.69                    |
| 21 cm $\times$ OSSK 515                               | 18.98                           | 14.12                        | 539.33             | 31.40                    |
| 21 cm $\times$ KORDUNA MR                             | 19.63                           | 14.34                        | 562.67             | 31.84                    |
| 21 cm $\times$ ZP 6263                                | 20.69                           | 14.77                        | 609.00             | 33.30                    |
| <b>LSD (0.05)</b>                                     | <b>1.5093<sup>a</sup></b>       | <b>0.3118<sup>a</sup></b>    | <b>0.2915</b>      | <b>0.107</b>             |
| <b>Starflow-CMZ <math>\times</math> Hybrid</b>        |                                 |                              |                    |                          |
| S0 $\times$ OSSK 515                                  | 17.19                           | 13.52                        | 424.00             | 28.48                    |
| S0 $\times$ KORDUNA MR                                | 17.87                           | 13.74                        | 445.33             | 28.91                    |
| S0 $\times$ ZP 6263                                   | 18.74                           | 14.14                        | 475.67             | 29.53                    |
| S1 $\times$ OSSK 515                                  | 17.80                           | 13.79                        | 482.67             | 30.47                    |
| S1 $\times$ KORDUNA MR                                | 18.46                           | 14.06                        | 507.33             | 31.14                    |
| S1 $\times$ ZP 6263                                   | 19.47                           | 14.48                        | 556.33             | 32.28                    |
| S2 $\times$ OSSK 515                                  | 18.07                           | 14.07                        | 532.67             | 31.47                    |
| S2 $\times$ KORDUNA MR                                | 18.74                           | 14.27                        | 555.00             | 32.30                    |
| S2 $\times$ ZP 6263                                   | 19.91                           | 14.76                        | 615.33             | 33.89                    |
| <b>LSD (0.05)</b>                                     | <b>1.4557<sup>a</sup></b>       | <b>0.3948<sup>a</sup></b>    | <b>0.2643</b>      | <b>0.1412</b>            |

<sup>a</sup> Corresponding ANOVA interaction term not statistically significant ( $P > 0.05$ ; Table 7); means shown for descriptive purposes only.

### 3.2.3. Three-way interaction: plant spacing $\times$ Starflow-CMZ $\times$ hybrid

The three-way interaction (Table 7) was not statistically significant for ear length ( $P = 1.000$ ) or rows per ear ( $P = 0.974$ ), but was highly significant for kernel number per ear and 100-kernel weight ( $P < 0.001$  in both cases). Kernel number per ear ranged from 359.00 (15 cm, S0, OSSK 515) to 664.00 (21 cm, S2, ZP 6263), an increase of 85% against an LSD of only 0.453, meaning that essentially every one of the 27 combinations differed significantly from all others. The 100-kernel weight ranged from 27.00 g to 34.87 g, with an LSD of 0.2245. The corresponding ear length (16.13–21.13 cm) and rows-per-ear (13.30–15.03) ranges shown in Table 10 followed the same general direction but, in the absence of a significant interaction term, should be attributed to the additive effect of the significant spacing and hybrid main effects rather than to a genuine three-way interaction. For kernel number per ear and 100-kernel weight, the single best-performing combination was consistently 21 cm spacing  $\times$  2 mL L<sup>-1</sup> Starflow-CMZ  $\times$  ZP 6263, and the poorest-performing combination was consistently 15 cm spacing  $\times$  0 mL L<sup>-1</sup> Starflow-CMZ  $\times$  OSSK 515.

**Table 10. Three-way interaction of plant spacing, Starflow-CMZ rate, and hybrid on yield components.**

| Spacing (cm)      | Starflow (mL L <sup>-1</sup> ) | Ear Length (cm) <sup>a</sup> |            |         | Rows per Ear <sup>a</sup> |            |         | Kernels per Ear |            |         |
|-------------------|--------------------------------|------------------------------|------------|---------|---------------------------|------------|---------|-----------------|------------|---------|
|                   |                                | OSSK 515                     | KORDUNA MR | ZP 6263 | OSSK 515                  | KORDUNA MR | ZP 6263 | OSSK 515        | KORDUNA MR | ZP 6263 |
| 15                | S0                             | 16.13                        | 16.83      | 17.60   | 13.30                     | 13.50      | 13.90   | 359.00          | 378.00     | 406.00  |
|                   | S1                             | 16.80                        | 17.43      | 18.47   | 13.50                     | 13.77      | 14.17   | 426.00          | 450.00     | 495.00  |
|                   | S2                             | 17.27                        | 17.97      | 19.13   | 13.87                     | 14.07      | 14.47   | 488.00          | 510.00     | 574.00  |
| 18                | S0                             | 16.97                        | 17.60      | 18.50   | 13.40                     | 13.60      | 14.07   | 420.00          | 440.00     | 474.00  |
|                   | S1                             | 17.47                        | 18.17      | 19.13   | 13.73                     | 14.07      | 14.47   | 482.00          | 510.00     | 558.00  |
|                   | S2                             | 17.60                        | 18.30      | 19.47   | 13.97                     | 14.17      | 14.77   | 525.00          | 547.00     | 608.00  |
| 21                | S0                             | 18.47                        | 19.17      | 20.13   | 13.87                     | 14.13      | 14.47   | 493.00          | 518.00     | 547.00  |
|                   | S1                             | 19.13                        | 19.77      | 20.80   | 14.13                     | 14.33      | 14.80   | 540.00          | 562.00     | 616.00  |
|                   | S2                             | 19.33                        | 19.97      | 21.13   | 14.37                     | 14.57      | 15.03   | 585.00          | 608.00     | 664.00  |
| <b>LSD (0.05)</b> |                                | <b>2.3688<sup>a</sup></b>    |            |         | <b>0.6057<sup>a</sup></b> |            |         | <b>0.453</b>    |            |         |

<sup>a</sup> Three-way interaction not statistically significant ( $P > 0.05$ ; Table 7); means shown for descriptive purposes only. 100-kernel weight, recorded for the same 27 combinations, ranged from 27.00 g (15 cm, S0, OSSK 515) to 34.87 g (21 cm, S2, ZP 6263), with an LSD of 0.2245, following the significant gradient reported above for kernel number per ear.

### 3.2.4. Discussion of yield component traits

The steep, near-multiplicative increase in kernel number per ear (from 381 to 619, +62%) under the combined effect of wider spacing and a higher Starflow-CMZ rate, and the highly significant two- and three-way interactions confirmed by ANOVA for this trait and for 100-kernel weight, mirror the well-documented sensitivity of kernel number to the interaction between plant density and nutrient or growth-input management in maize. Field studies combining planting density with nitrogen rate have shown that yield gains under improved management are driven mainly by increased kernel number per ear, and that this response depends jointly on both the spacing/density regime and the nutrient input rather than on either factor alone (Du et al., 2021). Canopy-level studies on nitrogen rate  $\times$  density interactions have similarly reported that nitrogen input increases kernel number and kernel weight most effectively when the crop is not simultaneously constrained by excessive competition for light and resources, matching the pattern observed here, in which the kernel-number and kernel-weight benefits of increasing Starflow-CMZ rate were most fully expressed at the widest spacing (21 cm) (Tian et al., 2022). Ear length and rows per ear, by contrast, were governed predominantly by the independent, additive effects of spacing and hybrid, without a significant interactive component.

This is consistent with the physiological basis of these two traits: ear length and row number are largely determined early in ear development, before kernel set is finalised, and are therefore less sensitive to the combined resource availability captured by the spacing  $\times$  nutrient  $\times$  genotype interaction than is final kernel number, which integrates resource supply throughout the grain-filling period (Du et al., 2021; Tian et al., 2022). The comprehensive superiority of ZP 6263 across all four yield components, expressed as a significant main effect in every case, supports the interpretation that this hybrid possesses an inherently greater capacity to convert assimilates into ear length, row number, kernel number, and kernel weight, consistent with genotype-by-environment interactions previously documented for yield-related traits in maize hybrid trials (Alam et al., 2022). The compounding three-way effect on kernel number per ear (nearly doubling, from 359 to 664, between the poorest and best combinations) indicates that, for this specific trait, kernel set is jointly limited by light and assimilate availability (governed by spacing), micronutrient supply (governed by Starflow-CMZ rate), and the genetic capacity of the hybrid to convert those resources into filled kernels; when all three factors are simultaneously favorable, their effects compound rather than simply add (Du et al., 2021).

### 3.3. Harvest index and total grain yield

#### 3.3.1. Analysis of variance and main effects

It was shown by analysis of variance (Table 11) that both harvest index and total grain yield were significantly affected by plant spacing, Starflow-CMZ rate, and hybrid, together with all of their two- and three-way interactions ( $P < 0.001$  in every case). It is therefore confirmed that, unlike several of the vegetative and yield-component traits discussed above, harvest index and total grain yield are governed by genuinely synergistic combinations of spacing, Starflow-CMZ rate, and hybrid rather than by additive main effects alone.

Harvest index increased progressively with wider spacing (41.06% at 15 cm to 41.86% at 21 cm) and with hybrid quality (39.30% for OSSK 515 to 43.45% for ZP 6263), and rose consistently with Starflow-CMZ rate, from 39.29% (S0) to 43.33% (S2) (Table 12). Total grain yield likewise increased with wider spacing (10.01 t ha<sup>-1</sup> at 15 cm to 13.67 t ha<sup>-1</sup> at 21 cm, a gain of approximately 37%) and with hybrid (10.78 t ha<sup>-1</sup> for OSSK 515 to 13.04 t ha<sup>-1</sup> for ZP 6263, a gain of approximately 21%). The response of total grain yield to Starflow-CMZ rate, however, was non-linear: yield rose from 11.63 t ha<sup>-1</sup> (S0) to a maximum of 11.94 t ha<sup>-1</sup> at the intermediate rate (S1), then declined slightly to 11.77 t ha<sup>-1</sup> at the highest rate (S2), indicating a plateau-type dose-response relationship rather than a strictly linear one.

**Table 11. Analysis of variance (significance levels) for harvest index and total grain yield.**

| Source of variation                           | d.f. | Harvest Index | Total Grain Yield |
|-----------------------------------------------|------|---------------|-------------------|
| Plant spacing (Distance)                      | 2    | ***           | ***               |
| Starflow-CMZ (Starflow)                       | 2    | ***           | ***               |
| Spacing $\times$ Starflow-CMZ                 | 4    | ***           | ***               |
| Hybrid (Cultivars)                            | 2    | ***           | ***               |
| Spacing $\times$ Hybrid                       | 4    | ***           | ***               |
| Starflow-CMZ $\times$ Hybrid                  | 4    | ***           | ***               |
| Spacing $\times$ Starflow-CMZ $\times$ Hybrid | 8    | ***           | ***               |

\*\*\* significant at  $P \leq 0.001$ .

**Table 12. Main effects of plant spacing, Starflow-CMZ rate, and hybrid on harvest index and total grain yield.**

| Factor / Level                          | Harvest Index (%) | Total Grain Yield (t ha <sup>-1</sup> ) |
|-----------------------------------------|-------------------|-----------------------------------------|
| <b>Plant spacing (cm)</b>               |                   |                                         |
| 15                                      | 41.06             | 10.01                                   |
| 18                                      | 41.31             | 11.67                                   |
| 21                                      | 41.86             | 13.67                                   |
| <b>LSD (0.05)</b>                       | <b>0.13243</b>    | <b>0.001679</b>                         |
| <b>Starflow-CMZ (mL L<sup>-1</sup>)</b> |                   |                                         |
| S0 (0)                                  | 39.29             | 11.63                                   |
| S1 (1)                                  | 41.62             | 11.94                                   |
| S2 (2)                                  | 43.33             | 11.77                                   |
| <b>LSD (0.05)</b>                       | <b>0.04352</b>    | <b>0.019091</b>                         |
| <b>Hybrid</b>                           |                   |                                         |
| OSSK 515                                | 39.30             | 10.78                                   |
| KORDUNA MR                              | 41.48             | 11.53                                   |
| ZP 6263                                 | 43.45             | 13.04                                   |
| <b>LSD (0.05)</b>                       | <b>0.03487</b>    | <b>0.002034</b>                         |

### 3.3.2. Two-way interactions

Spacing × Starflow-CMZ: harvest index increased consistently from 38.40% (15 cm × S0) to a maximum of 43.49% (15 cm × S2), with all nine combinations differing significantly (LSD = 0.13105). Total grain yield showed a more complex pattern: at 15 and 18 cm spacing, yield increased with Starflow-CMZ rate up to S1/S2, but at 21 cm spacing, yield was highest at S0 (14.13 t ha<sup>-1</sup>) and declined progressively at S1 (13.70 t ha<sup>-1</sup>) and S2 (13.16 t ha<sup>-1</sup>) (LSD = 0.027016; Table 13). This reversal at the widest spacing indicates that, once inter-plant competition is minimal, additional Starflow-CMZ input beyond the basal rate no longer translates into higher grain yield and may even become mildly counter-productive, consistent with a luxury-consumption or micronutrient-antagonism effect at low planting density (Jarecki et al., 2025).

Spacing × Hybrid: harvest index and grain yield both increased consistently with wider spacing for all three hybrids, with ZP 6263 numerically highest at every spacing level; grain yield ranged from 9.11 t ha<sup>-1</sup> (15 cm × OSSK 515) to 15.07 t ha<sup>-1</sup> (21 cm × ZP 6263) (LSD = 0.00312). Starflow-CMZ × Hybrid: harvest index increased from 37.49% (S0 × OSSK 515) to 45.87% (S2 × ZP 6263) (LSD = 0.06348); grain yield ranged from 10.65 t ha<sup>-1</sup> (S2 × OSSK 515) to 13.27 t ha<sup>-1</sup> (S2 × ZP 6263), with the overall maximum recorded for S1 × ZP 6263 (13.26 t ha<sup>-1</sup>) rather than S2 × ZP 6263, again reflecting the plateau in the Starflow-CMZ response (LSD = 0.019232; Table 13). As with the vegetative and yield-component traits, the second row originally labelled “S0 × OSSK 515” in this interaction corresponds to the 1 mL L<sup>-1</sup> rate (S1) combined with OSSK 515 and has been relabeled accordingly.

**Table 13. Two-way interactions of plant spacing × Starflow-CMZ, plant spacing × hybrid, and Starflow-CMZ × hybrid on harvest index and total grain yield.**

| Interaction                         | Harvest Index (%) | Total Grain Yield (t ha <sup>-1</sup> ) |
|-------------------------------------|-------------------|-----------------------------------------|
| <b>Plant spacing × Starflow-CMZ</b> |                   |                                         |
| 15 cm × S0                          | 38.40             | 9.30                                    |
| 15 cm × S1                          | 41.30             | 10.20                                   |
| 15 cm × S2                          | 43.49             | 10.54                                   |
| 18 cm × S0                          | 39.15             | 11.47                                   |
| 18 cm × S1                          | 41.61             | 11.93                                   |
| 18 cm × S2                          | 43.17             | 11.62                                   |
| 21 cm × S0                          | 40.31             | 14.13                                   |
| 21 cm × S1                          | 41.94             | 13.70                                   |
| 21 cm × S2                          | 43.32             | 13.16                                   |
| <b>LSD (0.05)</b>                   | <b>0.13105</b>    | <b>0.027016</b>                         |
| <b>Plant spacing × Hybrid</b>       |                   |                                         |

|                              |                |                 |
|------------------------------|----------------|-----------------|
| 15 cm × OSSK 515             | 38.87          | 9.11            |
| 15 cm × KORDUNA MR           | 41.12          | 9.80            |
| 15 cm × ZP 6263              | 43.19          | 11.13           |
| 18 cm × OSSK 515             | 39.13          | 10.65           |
| 18 cm × KORDUNA MR           | 41.48          | 11.44           |
| 18 cm × ZP 6263              | 43.33          | 12.92           |
| 21 cm × OSSK 515             | 39.90          | 12.58           |
| 21 cm × KORDUNA MR           | 41.85          | 13.35           |
| 21 cm × ZP 6263              | 43.82          | 15.07           |
| <b>LSD (0.05)</b>            | <b>0.1295</b>  | <b>0.00312</b>  |
| <b>Starflow-CMZ × Hybrid</b> |                |                 |
| S0 × OSSK 515                | 37.49          | 10.79           |
| S0 × KORDUNA MR              | 39.60          | 11.53           |
| S0 × ZP 6263                 | 40.76          | 12.59           |
| S1 × OSSK 515                | 39.49          | 10.91           |
| S1 × KORDUNA MR              | 41.66          | 11.65           |
| S1 × ZP 6263                 | 43.70          | 13.26           |
| S2 × OSSK 515                | 40.92          | 10.65           |
| S2 × KORDUNA MR              | 43.18          | 11.41           |
| S2 × ZP 6263                 | 45.87          | 13.27           |
| <b>LSD (0.05)</b>            | <b>0.06348</b> | <b>0.019232</b> |

### 3.3.3. Three-way interaction: plant spacing × Starflow-CMZ × hybrid

The three-way interaction was significant for both harvest index and total grain yield (Table 11; Table 14). Harvest index ranged from 36.57% (15 cm, S0, OSSK 515) to 46.16% (15 cm, S2, ZP 6263), with the highest values overall recorded at 21 cm spacing combined with ZP 6263 (up to 45.68%). Total grain yield ranged from 8.59 t ha<sup>-1</sup> (15 cm, S0, OSSK 515) to a maximum of 15.26 t ha<sup>-1</sup> at 21 cm, S0, ZP 6263. Notably, the single highest-yielding combination in the entire experiment was 21 cm spacing combined with no Starflow-CMZ and the hybrid ZP 6263 (15.26 t ha<sup>-1</sup>), rather than the combination that maximised vegetative growth and most yield components (21 cm × 2 mL L<sup>-1</sup> × ZP 6263, which yielded 14.71 t ha<sup>-1</sup>). At 21 cm spacing specifically, total grain yield declined monotonically as the Starflow-CMZ rate increased from S0 to S2 for all three hybrids (e.g., ZP 6263: 15.26 to 15.23 to 14.71 t ha<sup>-1</sup>), whereas at 15 and 18 cm spacing, yield still increased or plateaued with Starflow-CMZ rate. This spacing-dependent reversal in the yield response to Starflow-CMZ rate is the main driver of the plateau observed in the Starflow-CMZ main effect (Section 3.3.1) and indicates a genuine three-way interaction rather than a simple additive relationship.

**Table 14. Three-way interaction of plant spacing, Starflow-CMZ rate, and hybrid on harvest index and total grain yield.**

| Spacing (cm)      | Starflow (mL L <sup>-1</sup> ) | Harvest Index (%) |            |         | Grain Yield (t ha <sup>-1</sup> ) |            |         |
|-------------------|--------------------------------|-------------------|------------|---------|-----------------------------------|------------|---------|
|                   |                                | OSSK 515          | KORDUNA MR | ZP 6263 | OSSK 515                          | KORDUNA MR | ZP 6263 |
| 15                | S0                             | 36.57             | 38.52      | 40.11   | 8.59                              | 9.21       | 10.10   |
|                   | S1                             | 39.12             | 41.47      | 43.31   | 9.31                              | 9.97       | 11.31   |
|                   | S2                             | 40.94             | 43.36      | 46.16   | 9.44                              | 10.20      | 11.98   |
| 18                | S0                             | 37.35             | 39.59      | 40.51   | 10.64                             | 11.35      | 12.41   |
|                   | S1                             | 39.41             | 41.75      | 43.69   | 10.86                             | 11.68      | 13.23   |
|                   | S2                             | 40.64             | 43.10      | 45.78   | 10.46                             | 11.28      | 13.12   |
| 21                | S0                             | 38.57             | 40.70      | 41.67   | 13.13                             | 14.01      | 15.26   |
|                   | S1                             | 39.95             | 41.76      | 44.11   | 12.57                             | 13.31      | 15.23   |
|                   | S2                             | 41.20             | 43.08      | 45.68   | 12.04                             | 12.74      | 14.71   |
| <b>LSD (0.05)</b> |                                | <b>0.14731</b>    |            |         | <b>0.027319</b>                   |            |         |

### **3.3.4. Discussion of harvest index and total grain yield**

The consistently significant interactions among spacing, Starflow-CMZ rate, and hybrid for harvest index and total grain yield, in contrast to the largely additive behaviour of ear length and rows per ear, indicate that final grain yield integrates the combined outcome of all upstream physiological and yield-component responses rather than being determined by any single trait acting alone. This agrees with the general understanding that grain yield in maize is a composite trait shaped by the multiplicative interaction of kernel number, kernel weight, and the efficiency of dry-matter partitioning to the grain (harvest index), each of which is itself sensitive to plant density, nutrient supply, and genotype (Du et al., 2021; Ludemann et al., 2022; Tian et al., 2022).

The spacing-dependent reversal in the grain-yield response to Starflow-CMZ rate, whereby yield increased with Starflow-CMZ at narrow and intermediate spacing but declined at the widest spacing (21 cm), is the most agronomically significant finding of this section. At high planting density (15 and 18 cm), inter-plant competition for light and nutrients apparently limited the plant's baseline micronutrient status, so that additional Zn-Mn-Cu supply through Starflow-CMZ produced a consistent yield benefit. At the widest spacing (21 cm), where competition was already minimal and individual plants had greater access to soil-based nutrients and light, the additional foliar micronutrient supply beyond the basal rate (S0) provided no further yield benefit and was associated with a small decline, a pattern consistent with reports that foliar micronutrient over-application can induce nutrient antagonism or luxury consumption once plant demand is already satisfied by improved growing conditions (Jarecki et al., 2025). This suggests that Starflow-CMZ application should be tailored to planting density: it is most beneficial at closer spacing, where plants are more likely to be micronutrient-limited, and may be unnecessary, or even mildly detrimental to yield, at wider spacing under the conditions of this study.

The overall superiority of ZP 6263 in both harvest index and total grain yield, expressed as significant main effects and reinforced by significant interactions with spacing and Starflow-CMZ rate, confirms that this hybrid partitions assimilates to the grain more efficiently than OSSK 515 or KORDUNA MR across the full range of management conditions tested, consistent with the vegetative-growth and yield-component advantages already described in Sections 3.1 and 3.2

## **4. Conclusion**

The results of this study demonstrate that plant spacing, Starflow-CMZ foliar bio-stimulant rate, and hybrid selection each significantly affected every trait measured, from vegetative growth through yield components to total grain yield. However, analysis of variance showed that these three factors did not interact synergistically for all traits: plant height, flag leaf area, ear length, and rows per ear responded additively, with each factor contributing independently, whereas SPAD chlorophyll reading, kernel number per ear, 100-kernel weight, harvest index, and total grain yield showed genuine and, in most cases, highly significant two- and three-way interactions. This distinction is agronomically meaningful, as it indicates that the traits most directly linked to final grain yield are precisely those most sensitive to the joint management of spacing, micronutrient supply, and hybrid choice.

Widening plant spacing from 15 to 21 cm consistently improved vegetative growth, yield components, and total grain yield by reducing inter-plant competition, and the hybrid ZP 6263 consistently outperformed OSSK 515 and KORDUNA MR across nearly all traits, reflecting a superior

genetic capacity to convert available resources into vegetative growth and grain yield. The response to Starflow-CMZ rate, by contrast, was density-dependent: at 15 and 18 cm spacing, grain yield increased consistently with Starflow-CMZ rate, whereas at 21 cm spacing, the highest yield was already achieved without any Starflow-CMZ application, and additional doses provided no further benefit and were associated with a slight yield decline. This pattern suggests that the bio-stimulant compensates most effectively for the resource limitation imposed by close spacing and offers diminishing or negligible returns once inter-plant competition is relieved by wide spacing.

On the basis of these findings, the hybrid ZP 6263 grown at 21 cm plant spacing can be recommended as the most productive combination identified in this study for maximizing maize grain yield under the conditions tested, with a Starflow-CMZ rate of 1 mL L<sup>-1</sup> recommended as a general-purpose rate that reliably improves chlorophyll content, vegetative growth, and yield components across all spacings, while growers using wide spacing may reduce or omit Starflow-CMZ application without sacrificing grain yield. Because these conclusions are based on a single growing season and location, further multi-environment and multi-season trials are recommended to confirm the stability of these interactions, to clarify the physiological basis of the spacing-dependent Starflow-CMZ response, and to refine site-specific recommendations for plant spacing and Starflow-CMZ application across a broader range of maize hybrids and agro-ecological conditions.

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