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# Functional Data Analysis of Foliar Biostimulant Effects on Cucumber (Cucumis sativus) Yield Dynamics in Hydroponic Greenhouse Cultivation

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## INTRODUCTION

Cucumber (Cucumis sativus) is one of the main crops produced in the world (FAO, 2023). Mexico is the 4th largest producer and a major exporter (SIAP, 2024). This has led to the search for improvements in both quality and yield.

The use of biostimulants in agriculture has surged due to their ability to enhance nutrient use efficiency, stress tolerance, and crop productivity (Du Jardin, 2015). Seaweed extracts and micronutrient formulations (Mg, B, Zn) are widely applied, yet their temporal effects on yield formation remain understudied. Traditional statistical methods (e.g., ANOVA) treat yield measurements as discrete points, neglecting continuous growth patterns (Ramsay & Silverman, 2005).

Functional Data Analysis (FDA) addresses this gap by modeling yield trajectories as smooth curves, capturing dynamic treatment effects (Kokoszka & Reimherr, 2017). This approach has been applied in crop phenotyping (Yang et al., 2021) but not yet in biostimulant research.

To this end, the aim was applying FDA to evaluate the dynamic responses of cucumber to foliar biostimulants under greenhouse hydroponic conditions, two trends that are becoming increasingly common in the agricultural sector.

## METHODS

A randomized block design with four treatments and two repetitions was used (Table 1). Additionally, a nutrient solution with 14N, 1.5P, 7K, 8Ca, 2.5Mg and 3S was supplied during the production cycle for all treatments. Each treatment had a total of 120 plants.

Foliar fertilization was applied over the whole cycle, every 15 days, except for the formulations with a high concentration of Mg, B and Zn, which was stopped at the beginning of flowering, following manufacturer recommendations (YaraVita). Fruits were cut and collected from 15 randomly selected plants per treatment and repetition. Weight was registered and accumulated yield was calculated.

**Table 1.** Treatments used in the experiment and weight harvested per cut. Means that do not share letters indicate differences *between the cuts.*

| Treatment | Formulation | Dosage | Cut 1 (kg) | Cut 2 (kg) | Cut 3 (kg) | Cut 4 (kg) |
|---|---|---|---|---|---|---|
| T1 (control) | Water | 2 L/ha | 4.04 b | 4.65 b | 4.82 ab | 9.19 a |
| T2 | Algal extract with bioactive compounds from *Ascophyllum nodosum*, N, K, B and Zn | | 4.18 b | 5.05 b | 7.76 ab | 10.46 a |
| T3 | Foliar formulation with a high concentration of Mg, B and Zn | | 4.098 b | 6.48 b | 7.35 ab | 9.50 a |
| T4 | A 1:1 mixture of T2 and T3 | 2 L/ha + 2 L/ha | 5.75 b | 5.31 b | 7.66 ab | 9.72 a |

Raw yield data were converted into continuous functions using B-spline expansions (Ramsay & Silverman, 2005) and functional principal component analysis (FPCA) was used to decompose yield trajectories into principal components for each treatment. A Functional ANOVA was applied to test treatment effects. Repeated measures ANOVA was also applied for comparison. Differences were considered significant with an α of 0.05.

## FUTURE WORK / REFERENCES

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## RESULTS & DISCUSSION

Figure 1a shows the cumulative productivity data of the four treatments, along with the mean smoothed germination curves (lines). The curves reflect the dynamics of the fruit production and related patterns for each treatment. The adjustment with B-Splines revealed that the best-fit curve for is linear splines, with one knot after the second cut. This illustrates the yield response of cucumber, showing constant growth without abrupt changes (Figure 2b).

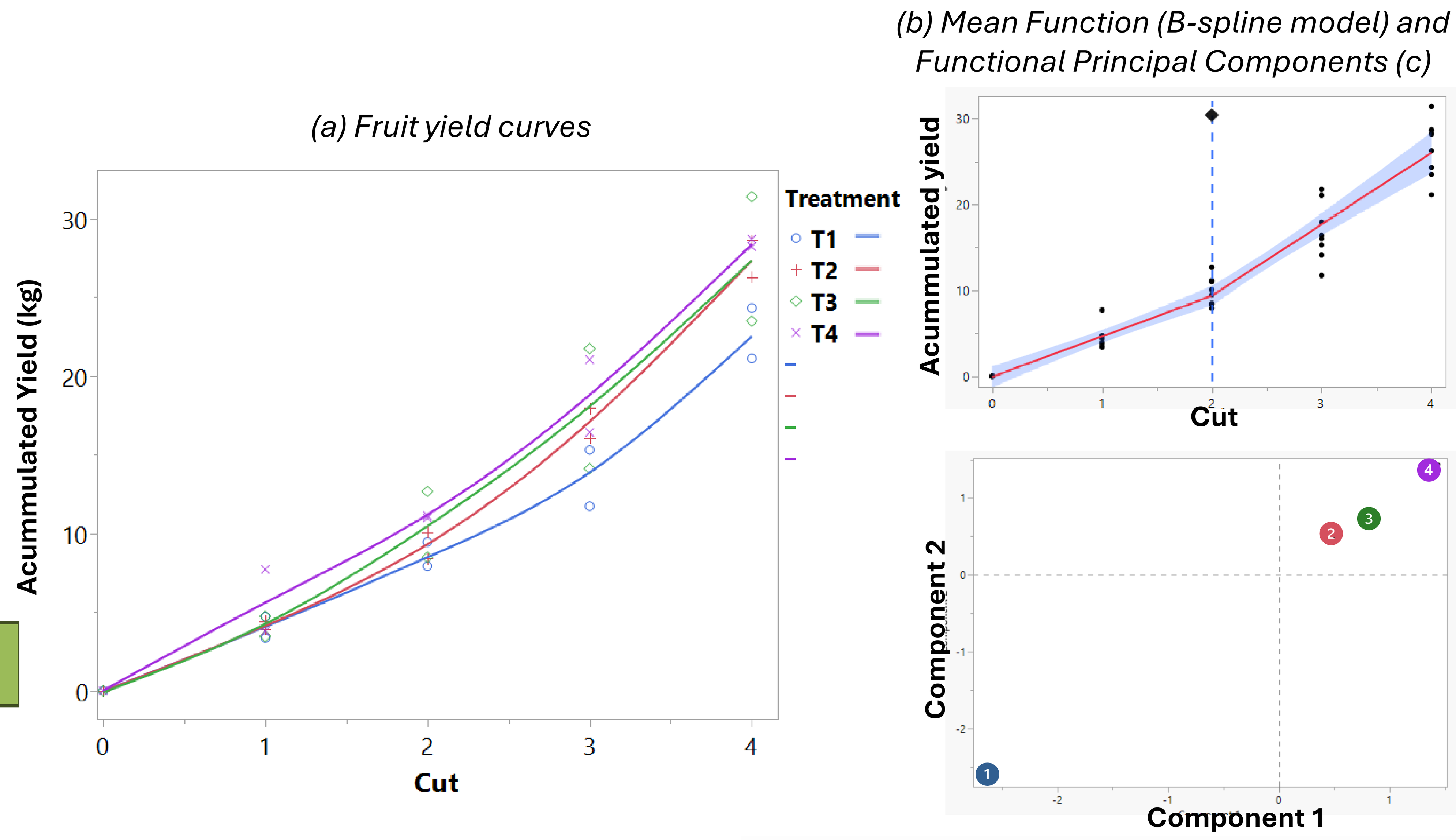


**Figure 1.** Fruit productivity dynamics of cucumber under different foliar biostimulant treatments.

The FPC analysis revealed that one component explained at least 94.3% of the variability in the curves, with all the curves exhibiting similar shapes. The major variation mode could be associated with an increased response or acceleration between the second and third cut, particularly for T4. The scoreplot also showed a separation of the treatments and control (Figure 1c).

Functional ANOVA revealed significant ($p = 0.04$) treatment effects, an interaction effect between number of cut and treatment, and also significant differences between cuts 2 and 3. For comparison, repeated measures ANOVA could not identify a significant treatment effect ($P=0.566$) or an interaction effect, as total harvest weight per cut was not affected by the application of biostimulants (Table 1, $P \geq 0.9$). A significant difference was found between the cuts, especially cut 4 (Table 1).

The early-phase acceleration in yield for T4 suggests that the combination of these biostimulant components synergistically promotes initial growth and fruit development, leading to optimized productivity (Khoulati et al., 2025; Skapste et al., 2025; Zuluaga et al., 2025).

## CONCLUSION

The results highlight the superior sensitivity of FDA in capturing subtle, continuous effects over point-in-time measurements, providing a more comprehensive understanding of biostimulant efficacy. Further research using FDA to model the complex dose-response relationships of biostimulants could provide a more nuanced understanding of their mechanisms.