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Review

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**YIELDS OF CUCUMBER HYBRIDS
AND FRUIT HARVESTING STANDARDS DEPENDING
ON THE USE OF BIOLOGICAL PRODUCTS
AND MICRONUTRIENTS UNDER DRIP IRRIGATION CONDITIONS
IN THE SOUTHERN STEPPE OF UKRAINE****O.V. Medonchak, L.G. Khonenko**

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Cucumber (*Cucumis sativus* L.) yield in the Southern Steppe of Ukraine depends on the hybrid, weather and the biological and micronutrient support of the crop. The study evaluated the yield of cucumber hybrids for different fruit harvesting standards depending on biopreparations and micronutrient fertilizers applied by fertigation under drip irrigation. A four-factor field experiment (2023–2025, Mykolaiv National Agrarian University) included hybrid (Kibria F1, Madeira F1), biopreparation (control, Azotofit, Organic-Balance), micronutrient fertilizer (control, Rostok Cucumber, Quantum PLATINUM) and fruit harvesting standard (piculi SS, gherkins LS, greens TR). Hydrothermal conditions differed sharply: 2023 was favourable (HTC 0,48–0,52), 2024 extremely dry (HTC 0,25–0,28) and 2025 moderately dry (HTC 0,32–0,38). Averaged over years and standards, yield ranged from 30,85 t/ha (Kibria F1, control) to 46,79 t/ha (Madeira F1 + Organic-Balance + Quantum PLATINUM; +51,7 %). Madeira F1 exceeded Kibria F1 by 4,64 t/ha (12,9 %), and its relative advantage increased from 9,8 % in 2023 to 15,2 % in the dry years. Organic-Balance increased yield by 12,4–12,9 % and Quantum PLATINUM by 17,7–19,9 % relative to the control; the advantage of Quantum PLATINUM over Rostok Cucumber was significant for factor means but not in all individual combinations. The response to the preparations and its statistical reliability increased in the order SS → LS → TR, whereas SS was the most drought-sensitive fraction (–29,2...–37,9 % in 2024). The combination Organic-Balance + Quantum PLATINUM applied by fertigation is recommended for Madeira F1 as an element of adaptive technology under drip irrigation.

Keywords: cucumber, hybrid, biopreparations, micronutrient fertilizers, drip irrigation, fertigation, yield, fruit harvesting standards, Southern Steppe of Ukraine.

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Урожайність гібридів та стандарт збору плодів огірка залежно від застосування біопрепаратів та мікродобрив за умов краплинного зрошення в Південному Степу України

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Урожайність огірка (*Cucumis sativus* L.) у Південному Степу України залежить від гібрида, погодних умов та біологічного й мікроелементного супроводу посівів. Мета досліджень – оцінити врожайність гібридів огірка за різних стандартів збирання плодів залежно від біопрепаратів і мікродобрив, внесених фертигацією за краплинного зрошення. Чотирифакторний польовий дослід проводили у 2023–2025 рр. у Миколаївському національному аграрному університеті: гібрид (Кібрія F1, Мадейра F1), біопрепарат (контроль, Азотофіт, Органік-баланс), мікродобриво (контроль, Росток огірки, Квантум ПЛАТИНУМ) і стандарт збирання плодів (пікулі SS, корнішони LS, зеленці TR). Роки істотно різнилися за гідротермічними умовами: 2023 р. був сприятливим (ГТК 0,48–0,52), 2024 р. – екстремально посушливим (ГТК 0,25–0,28), 2025 р. – помірно посушливим (ГТК 0,32–0,38). У середньому за три роки та стандартами збирання врожайність становила від 30,85 т/га (Кібрія F1, контроль) до 46,79 т/га (Мадейра F1 + Органік-баланс + Квантум ПЛАТИНУМ; +51,7 %). Гібрид Мадейра F1 перевищував Кібрию F1 на 4,64 т/га (12,9 %), а його відносна перевага зростала з 9,8 % у 2023 р. до 15,2 % у посушливі роки. Органік-баланс підвищував урожайність на 12,4–12,9 %, Квантум ПЛАТИНУМ – на 17,7–19,9 %; перевага Квантум ПЛАТИНУМ над Ростком огірки була істотною для середніх за фактором, але не в усіх окремих комбінаціях. Реакція на препарати та її статистична надійність зростали в ряду SS → LS → TR, а фракція SS була найчутливішою до посухи (–29,2...–37,9 % у 2024 р.). Поєднання Органік-баланс + Квантум ПЛАТИНУМ, внесені фертигацією, рекомендовано для гібрида Мадейра F1 як елемент адаптивної технології вирощування огірка за краплинного зрошення.

Ключові слова: огірок, гібрид, біопрепарати, мікродобрива, краплинне зрошення, фертигація, урожайність, стандарти збирання плодів, Південний Степ України.

Introduction. Cucumber (*Cucumis sativus* L.) remains one of the leading vegetable crops of world and domestic vegetable growing owing to high consumer demand, versatility of use and a relatively short period of formation of a marketable yield [19, 21]. The crop steadily holds a stable position among the most marketable vegetable products, and the genetic improvement of hybrids over recent decades has substantially expanded the possibilities of their adaptation to different soil-and-climate conditions [15, 21]. For Ukraine, cucumber is a traditional crop of both open and protected ground, the produce of which is in demand both on the fresh-vegetable

market and in the processing industry [5, 11, 12].

At the same time, the economic value of cucumber is determined not only by the gross harvest of fruit, but also by the marketable structure of the yield – the ratio of fractions of different size and purpose, each of which has its own market value, quality requirements and harvesting technology [9, 12]. In production practice, at least three main marketable standards of cucumber fruit are distinguished: piculi (SS) – the smallest and earliest fraction; gherkins (LS) – processing produce of intermediate size; and greens (TR) – the largest fraction by mass, of table use. At a similar level

of yield, technological treatments may differ substantially precisely in the output of these fractions, which directly affects the economic performance of production [12, 30].

Realizing the productive potential of modern cucumber hybrids in the Southern Steppe zone of Ukraine is complicated by the progressive aridization of the climate – an increase in the frequency and intensity of temperature anomalies, a reduction and irregularity of atmospheric precipitation, and the intensification of drought phenomena during the phases of flowering and fruit set that are critical for the crop. Drip irrigation is today an obligatory element of cucumber-growing technology in the region, and fertigation through drip systems has proved effective for supplying nutrients to various crops in the south of Ukraine [3, 6]; however, irrigation on its own compensates primarily for the deficit of soil moisture and does not eliminate the suppressive effect of atmospheric drought and overheating of the plants' assimilation apparatus [16, 23, 26]. In this connection, the search for additional technological elements capable of increasing the adaptability of plants to stress growing conditions is acquiring ever greater importance.

According to FAO data, world production of cucumbers and gherkins in 2022 exceeded 84 million t, with the main volume (79,4 %) formed by China, while Ukraine, with a production volume of about 1,04 million t (1,2 % of world production), was steadily among the ten leading producing countries [19]. At the same time, during 2019–2021 the area under cucumber in Ukraine decreased from 48,2 to 45,4 thousand ha at a practically unchanged volume of gross production (1,04–1,05 million t), which reflects the general trend of intensification of the crop – an increase in the average fruit yield against a reduction of the sown area [4]. The share of greenhouse fruit production over this period grew from 25 to 28 %, whereas that of open ground decreased from 75 to 72 %, which emphasizes the growing competition between protected- and open-ground technologies and the relevance of increasing the efficiency of the

latter through agrochemical and biological factors of intensification [4].

One of the promising ways of solving this task is the application of biopreparations based on rhizosphere microorganisms (*Azotobacter*, *Bacillus subtilis*, *Azospirillum*) and chelated micronutrient fertilizers. Biopreparations activate the development of the root system [14, 13, 28], enhance nitrogen fixation and phosphorus mobilization [14, 22] and induce systemic resistance of plants to abiotic stresses [13, 24, 28]. Micronutrient fertilizers in chelated form ensure the prompt supply of plants with zinc, boron, manganese and other trace elements [20, 27, 29] that are directly involved in photosynthesis, enzymatic reactions and the formation of generative organs [17, 18], especially during periods when the efficiency of root nutrition declines because of unfavourable weather conditions [25, 31]. The effectiveness of the combined application of biopreparations and micronutrient fertilizers has been confirmed for a number of field crops in Ukraine [1, 2]; however, for cucumber hybrids under drip irrigation in the conditions of the Southern Steppe of Ukraine, with differentiation by fruit harvesting standards, such studies are limited and fragmentary.

In modern vegetable growing, the concept of adaptive technology is gaining increasing recognition; it is based on the fullest possible harmonization of the biological features of the crop with environmental conditions and the system of agrotechnical measures [5, 9]. For cucumber, the implementation of this approach involves not only the selection of a high-yielding and drought-tolerant hybrid, but also the creation of an optimal background of water and nutrient supply, as well as the application of regulatory elements capable of maintaining the functional activity of plants under stress conditions [9, 11]. A review of the available literature shows that the effectiveness of individual micronutrient fertilizers and biopreparations on cucumber has been studied mainly under protected-ground conditions [13, 17, 24], whereas their combined action on open-ground hybrids under the contrasting arid conditions

of the Southern Steppe of Ukraine, with differentiation by marketable produce standards, remains insufficiently studied, which determined the relevance of the present research.

The aim of the research was to establish the regularities of the formation of yield and marketable fruit structure of cucumber hybrids (Kibria F1, Madeira F1) depending on the application of biopreparations (Azotofit, Organic-Balance) and micronutrient fertilizers (Rostok Cucumber, Quantum PLATINUM) applied by fertigation under drip irrigation in the contrasting hydrothermal conditions of 2023–2025 in the Southern Steppe zone of Ukraine, and to identify the most effective combination of the studied factors.

Materials and methods. The research was carried out during 2023–2025 at the experimental field of the Educational,

Scientific and Practical Centre of Mykolaiv National Agrarian University, located in the Southern Steppe zone of Ukraine. The soil cover of the experimental plot is represented by a southern low-humus, slightly solonetzic, heavy-loamy chernozem on loess parent rocks, with a humus content in the arable layer of 2,9–3,15 % (by Tyurin), medium supply of mobile phosphorus (38 mg/kg by Chyrykov) and an elevated content of exchangeable potassium (332–525 mg/kg by Maslova); the reaction of the soil solution is neutral (pH 6,8–7,2 in the 0–30 cm layer).

The weather conditions of the study years differed substantially in their hydrothermal regime (Table 1), which made it possible to assess the response of the hybrids and the effectiveness of the agrochemical agents over a wide range of abiotic load [2].

1. Weather conditions of the 2023–2025 growing seasons compared with the climatic norm (Mykolaiv weather station)

Indicator	Norm 1991–2020	2023	2024	2025
Mean temperature of the growing season (IV–X), °C	18,3	19,7	22,5	19,4
Absolute maximum temperature, °C	34,5	36,0	41,6	39,6
Precipitation total, IV–X, mm	301	285	161	192
Share of the long-term precipitation norm, %	100	95	53	64
HTC for May–September	0,50	0,48–0,52	0,25–0,28	0,32–0,38
Season characteristic	norm	favourable	extremely dry	moderately dry

Note: compiled from data of the Mykolaiv Hydrometeorological Centre. HTC – Selyaninov hydrothermal coefficient.

The experiment was established according to a four-factor design: factor A – cucumber hybrid (Kibria F1, Madeira F1); factor B – biopreparation (control – water treatment, Azotofit, Organic-Balance); factor C – micronutrient fertilizer (control – water treatment, Rostok Cucumber, Quantum PLATINUM); and factor D – marketable fruit standard, i.e. fruit-harvesting regime (SS – piculi, LS – gherkins, TR – greens). Yield was determined separately for the three marketable fruit standards: piculi (SS); gherkins (LS, diameter 3,0–3,5 cm, mass 30–55 g); and greens (TR, length 9–12 cm, harvesting duration 56–72 days). Since each marketable

standard corresponded to a separate fruit-harvesting regime, the yields of the SS, LS and TR standards are alternative rather than additive; therefore, the mean value across the three standards (factor D) is used below as an integral indicator of yield. The hybrid Kibria F1 (Rijk Zwaan) is an ultra-early parthenocarpic hybrid of the gherkin type, with a period from transplanting to the onset of fruiting of 35–38 days; the hybrid Madeira F1 (Seminis) is an early parthenocarpic hybrid adapted to arid and thermally unstable conditions, with the corresponding period of 40–45 days [8].

The plants were grown by the seedling method according to a 200 × 26,5 cm scheme (20,3 thousand plants/ha) against a background of drip irrigation with a seasonal irrigation norm of 3810–6720 m³/ha depending on the year. Biopreparations and micronutrient fertilizers were applied exclusively by fertigation (root application through the drip-irrigation system); no foliar treatments were carried out. In the control treatments of factors B and C, irrigation water without preparations was supplied. In the treatments with biopreparations the rate of mineral nitrogen was reduced by 25–30 % compared with the control, taking into account potential nitrogen fixation.

Azotofit, a preparation based on nitrogen-fixing bacteria, and Organic-Balance, whose action is based on the combination of the bacteria *Azospirillum brasilense* and *Bacillus subtilis*, which enhance nitrogen fixation, phosphorus mobilization and the formation of induced systemic resistance of plants [1, 4, 12], were used as biopreparations. Rostok Cucumber and Quantum PLATINUM – complexes of chelated trace elements (zinc, boron, manganese, iron) intended for the optimization of micronutrient nutrition during the critical phases of growth and

fruit set [18, 20, 25] – were used as micronutrient fertilizers. All preparations were applied at the rates specified in the manufacturers' regulations, by fertigation through the drip-irrigation system.

Yield accounting was performed by continuous harvesting of fruit from each accounting plot (72 m²) separately for each replication (threefold replication, systematic arrangement of treatments). Statistical processing of the results was carried out by analysis of variance (ANOVA) with determination of the least significant difference (LSD₀₅) in Statistica 10 and Microsoft Excel 2019, in accordance with generally accepted field-experiment methods [26, 27]. LSD₀₅ values are given in the notes to Tables 2–6: for individual years (Tables 2–4) and as the range of annual values for 2023–2025 (Tables 5, 6). For the three-year means, a difference was considered significant only if it exceeded the upper limit of this range; Tables 7 and 8 present treatment means.

Results and discussion. Yield formation in the earliest and most nutrition-sensitive marketable fraction, piculi (SS), in the hydrothermally favourable year 2023 depended on all three studied factors (Table 2).

2. Yield of cucumber fruit (piculi, SS) depending on the hybrid, biopreparation and micronutrient fertilizer, 2023, t/ha

Hybrid (factor A)	Biopreparation (factor B)	Micronutrient fertilizer (factor C)			Mean for factor C
		control – water treatment	Rostok Cucumber	Quantum PLATINUM	
Kibria F1	control – water treatment	32,610	34,698	36,158	34,487
	Azotofit	34,224	36,842	37,877	36,316
	Organic-Balance	35,329	38,114	39,395	37,614
	Mean for factor B	34,057	36,553	37,807	36,141
Madeira F1	control – water treatment	36,978	38,378	40,329	38,562
	Azotofit	38,456	40,623	42,141	40,408
	Organic-Balance	40,136	41,952	43,812	41,970
	Mean for factor B	38,522	40,316	42,097	40,312

Note: planting scheme 200×26,5 cm, 20 300 plants/ha; drip irrigation; HTC in 2023 – 0,48–0,52. LSD₀₅, t/ha: A – 1,58; B – 0,87; C – 1,35; AB – 1,78; BC – 1,44; AC – 1,74; ABC – 2,09. Marginal means for factor B are given in bold.

Hybrid Madeira F1 produced a mean yield of 40,312 t/ha compared with 36,141 t/ha for hybrid Kibria F1 (+4,171 t/ha, or 11,5 %, at LSD₀₅ for factor A of 1,58 t/ha), which may be attributed to its higher heterotic potential and greater density of female flowers on first-order

shoots [15, 30]. The advantage of Madeira F1 was significant in each of the nine combinations of biopreparation and micronutrient fertilizer (3,68–4,81 t/ha at LSD₀₅ for the ABC interaction of 2,09 t/ha). The lowest fruit yield was recorded in the

control treatment of hybrid Kibria F1 (32,610 t/ha) and the highest in the combination Madeira F1 + Organic-Balance + Quantum PLATINUM (43,812 t/ha); the difference between these extreme treatments (11,202 t/ha) was 5,4 times greater than LSD_{05} for the ABC interaction.

Averaged over hybrids and micronutrient fertilizers, piculi yield was 36,52 t/ha in the control, 38,36 t/ha with Azotofit and 39,79 t/ha with Organic-Balance; all pairwise differences (1,43–3,27 t/ha) exceeded LSD_{05} for factor B (0,87 t/ha). Within each hybrid (AB interaction, $LSD_{05} = 1,78$ t/ha), both biopreparations significantly exceeded the control: Azotofit by 1,83–1,85 t/ha and Organic-Balance by 3,13–3,41 t/ha (from 34,487 to 37,614 t/ha, or by 9,1 %, in Kibria F1 and from 38,562 to 41,970 t/ha, or by 8,8 %, in Madeira F1). The advantage of Organic-Balance over Azotofit within individual hybrids (1,30–1,56 t/ha) did not exceed LSD_{05} for the AB interaction and should be regarded as a tendency. The higher efficacy of Organic-Balance may be explained by its combination of nitrogen-fixing and phosphate-mobilizing bacteria, which stimulate root growth and root exudation and thereby enhance the uptake of nutrients, including trace elements, from the root zone [13, 14, 22].

For factor C, mean piculi yield was 36,29 t/ha in the control, 38,43 t/ha with Rostok Cucumber and 39,95 t/ha with Quantum PLATINUM. Both micronutrient fertilizers significantly increased yield relative to the control (by 2,15 and 3,66 t/ha at LSD_{05} for factor C of 1,35 t/ha), and the advantage of Quantum PLATINUM over Rostok Cucumber averaged over the factor (1,52 t/ha) also exceeded LSD_{05} . When the fertilizers are compared within an individual hybrid, the appropriate criterion is LSD_{05} for the AC interaction (1,74 t/ha) rather than for the main effect of C, since such means are based on half as many observations [7, 10]. By this criterion, the advantage of Quantum PLATINUM over Rostok Cucumber was significant in Madeira F1 (1,78 t/ha) and non-significant in Kibria F1 (1,25 t/ha). In individual hybrid ×

biopreparation combinations, the difference between these fertilizers was 1,04–1,95 t/ha, i.e. below LSD_{05} for the ABC interaction (2,09 t/ha), whereas the advantage of Quantum PLATINUM over the control (3,35–4,07 t/ha) was significant in all six combinations. The direction of the micronutrient effect is consistent with published data on the efficacy of trace elements in cucumber [17, 27, 29].

Thus, for the SS fraction in 2023, the significance of the effects of hybrid, biopreparation and micronutrient fertilizer was confirmed at the level of main effects, as well as for the comparison of each preparation with the control. At the same time, some differences between adjacent factor levels within individual combinations (Organic-Balance vs Azotofit, Quantum PLATINUM vs Rostok Cucumber) did not exceed LSD_{05} . This is to be expected for the fraction with the smallest fruit mass, in which the absolute yield increments from the preparations are smallest. Therefore, in the subsequent analysis, differences between treatments were evaluated against LSD_{05} for the corresponding level of interaction, and differences smaller than LSD_{05} were treated as tendencies.

The 2024 growing season was the most stressful of the study period: the hydrothermal coefficient for May–September was only 0,25–0,28, 18 days with daily maxima above +37 °C and an absolute maximum of +41,6 °C were recorded, and the precipitation deficit in June–August reached 78 % of the norm. Under these conditions, piculi yield decreased by 29,2–37,9 % compared with 2023, depending on the treatment (Table 3); the largest decrease occurred in the control treatment of hybrid Kibria F1 (–37,9 %) and the smallest in the combination Madeira F1 + Organic-Balance (–29,2 %).

The effects of the studied factors remained significant even under extreme conditions. The advantage of hybrid Madeira F1 amounted to 4,35–5,73 t/ha (LSD_{05} for the AB interaction = 1,47 t/ha), and both biopreparations significantly exceeded the control in both hybrids (by 1,95–3,98 t/ha); the increment from Organic-Balance was 12,1 % in Kibria F1 and 15,4 % in Madeira F1. The

advantage of Organic-Balance over Azotofit was significant in Madeira F1 (1,83 t/ha) and non-significant in Kibria F1 (0,65 t/ha). The smaller relative yield decline in hybrid Madeira F1 (–29,2...–33,2 %

against –35,7...–37,9 % in Kibria F1) indicates its higher heat tolerance and better ability to retain fruit set and continue fruiting under stress [15, 30].

3. Yield of piculi (SS) by hybrids and biopreparations in the contrasting years 2023 and 2024 (mean across micronutrient fertilizers), t/ha

Hybrid (factor A)	Biopreparation (factor B)	2023 (favourable)	2024 (extreme drought)	Change in 2024 vs 2023, %
Kibria F1	control – water treatment	34,487	21,400	–37,9
	Azotofit	36,316	23,350	–35,7
	Organic-Balance	37,614	23,995	–36,2
Madeira F1	control – water treatment	38,562	25,750	–33,2
	Azotofit	40,408	27,895	–31,0
	Organic-Balance	41,970	29,725	–29,2

Note: compiled from field experiment data (mean across the three levels of factor C). LSD₀₅, t/ha: 2023: A – 1,58; B – 0,87; AB – 1,78; 2024: A – 1,19; B – 0,55; AB – 1,47.

The direction of the factors' effects in the other marketable fractions was the same, but the absolute magnitude of the effects increased with fruit size. In 2023, mean gherkin (LS) yield was 51,234 t/ha in hybrid Madeira F1 against 45,781 t/ha in Kibria F1 (+5,453 t/ha),

and greens (TR) yield was 61,455 against 57,414 t/ha (+4,041 t/ha); the advantage of Madeira F1 was significant with each biopreparation (3,46–5,66 t/ha at LSD₀₅ for the ABD interaction of 2,45 t/ha; Table 4).

4. Yield of gherkins (LS) and greens (TR) depending on the hybrid and biopreparation, 2023, t/ha

Hybrid (factor A)	Biopreparation (factor B)	Fruit harvesting standard (factor D)	
		Gherkins (LS)	Greens (TR)
Kibria F1	control – water treatment	43,206	52,807
	Azotofit	45,685	57,281
	Organic-Balance	48,452	62,154
Madeira F1	control – water treatment	48,342	57,755
	Azotofit	51,343	60,996
	Organic-Balance	54,018	65,615

Note: planting scheme 200×26,5 cm, 20 300 plants/ha; drip irrigation; HTC in 2023 – 0,48–0,52. LSD₀₅, t/ha: A – 1,58; B – 0,87; D – 1,91; AB – 1,78; BD – 2,23; AD – 1,74; ABD – 2,45.

The range between the extreme treatments in the LS fraction (40,535...57,492 t/ha) exceeded that of the SS fraction, indicating a fuller realization of the effect of the preparations during mass fruiting, when not only fruit set but also retention of the set fruit and uninterrupted fruit filling become decisive [30, 32]. In the greens (TR) fraction, which provides the largest harvest per season, the highest yield was obtained in the combination Madeira F1 + Organic-Balance +

Quantum PLATINUM (72,518 t/ha), 21,9 % higher than the corresponding micronutrient control.

Unlike piculi, in the LS and TR fractions in 2023 all pairwise differences between biopreparation levels within each hybrid exceeded LSD₀₅ for the ABD interaction (2,45 t/ha). The difference between the control and Organic-Balance was 3,13–3,41 t/ha in piculi, 5,25–5,68 t/ha in gherkins and 7,86–9,35 t/ha in greens, and that between

Organic-Balance and Azotofit was 1,30–1,56 (non-significant), 2,68–2,77 and 4,62–4,87 t/ha, respectively. Hence, the absolute response to biopreparations increases in the order SS → LS → TR. This agrees with the view that the prolonged formation of the large-fruited fraction requires sustained and stable nutrition, which is most fully provided by combining a biopreparation with a chelated micronutrient fertilizer [28, 30, 32].

In 2025, which was intermediate in terms of hydrothermal conditions (HTC 0,32–0,38), crop productivity partly recovered: gherkin (LS) yield was 31,305 t/ha in Kibria F1 and 35,410 t/ha in Madeira F1, and greens (TR) yield was 37,120 and 42,270 t/ha, respectively, without reaching the 2023 level. The ranking of treatments by the efficacy of the preparations was the same in all study years; the statistical evaluation of differences for the three-year means is presented below (Tables 5, 6).

Generalization of the three-year data (2023–2025) makes it possible to differentiate the contribution of controllable factors (genotype, biopreparations, micronutrient fertilizers) and uncontrollable factors (weather conditions of the year) to crop productivity (Tables 5, 6). For the three-year means, the

table notes give the range of LSD₀₅ values across the study years; a difference was considered significant only if it exceeded the upper limit of this range, i.e. the largest of the annual LSD₀₅ values (a conservative criterion). On average over 2023–2025, hybrid Madeira F1 outyielded Kibria F1 for all marketable standards: by 16,4 % in the SS fraction (33,141 vs 28,475 t/ha), by 12,6 % in LS (40,018 vs 35,535 t/ha) and by 10,9 % in TR (48,677 vs 43,896 t/ha); with each biopreparation, this advantage (3,97–5,49 t/ha) exceeded the upper limit of LSD₀₅ for the ABD interaction (2,45 t/ha). The consistent decrease in the relative advantage of Madeira F1 with increasing fruit size indicates that the early small-fruited fraction is the most sensitive indicator of genotype adaptability to stress, whereas the large-fruited TR fraction is the best indicator of the crop's response to intensified mineral and micronutrient nutrition [30, 32]. Among the biopreparations, averaged over three years and the three marketable standards, Organic-Balance was the most effective: the yield increment relative to the control was 4,344 t/ha (12,9 %) in Kibria F1 and 4,759 t/ha (12,4 %) in Madeira F1 (Table 5).

5. Yield of cucumber fruit by marketable standards depending on the hybrid and biopreparation (mean for 2023–2025), t/ha

Hybrid (factor A)	Biopreparation (factor B)	Fruit harvesting standard (factor D)			Mean for factor D
		SS	LS	TR	
Kibria F1	control – water treatment	27,372	33,485	40,499	33,786
	Azotofit	28,569	35,537	43,840	35,982
	Organic-Balance	29,458	37,576	47,356	38,130
	Mean for factor B	28,475	35,535	43,896	35,969
Madeira F1	control – water treatment	31,346	37,824	45,630	38,267
	Azotofit	33,139	39,971	48,539	40,550
	Organic-Balance	34,947	42,273	51,858	43,026
	Mean for factor B	33,141	40,018	48,677	40,612

Note: marginal means for factor B are given in bold. Compiled from field experiment data. LSD₀₅ (range for 2023–2025), t/ha: A – 1,08–1,58; B – 0,51–0,87; D – 1,66–1,91; AB – 1,47–1,78; BD – 1,92–2,23; AD – 1,34–1,74; ABD – 2,13–2,45.

Within each hybrid, all pairwise differences between factor B levels, including the advantage of Organic-Balance over Azotofit (2,15–2,48 t/ha), exceeded the upper limit of LSD₀₅ for the AB interaction

(1,78 t/ha). The effect of the biopreparations differed clearly between marketable standards (ABD interaction, upper limit of LSD₀₅ = 2,45 t/ha). In the TR fraction all pairwise differences were significant

(2,91–6,86 t/ha). In the LS fraction only the advantage of Organic-Balance over the control was significant (4,09–4,45 t/ha). In the SS fraction only the advantage of Organic-Balance over the control in Madeira F1 was significant (3,60 t/ha), whereas in Kibria F1 it (2,09 t/ha) was below LSD_{05} . This is consistent with evidence that combinations of nitrogen-fixing and phosphate-mobilizing strains induce systemic resistance in plants and enhance

nutrient uptake under abiotic stress [14, 22, 28].

Of the micronutrient fertilizers, Quantum PLATINUM made the greater contribution to yield formation (Table 6): the yield increment relative to the control was 6,508 t/ha (19,9 %) in Kibria F1 and 6,592 t/ha (17,7 %) in Madeira F1, and its advantage over Rostok Cucumber (3,00–3,13 t/ha) exceeded the upper limit of LSD_{05} for the AC interaction (1,74 t/ha).

6. Yield of cucumber fruit by marketable standards depending on the hybrid and micronutrient fertilizer (mean for 2023–2025), t/ha

Hybrid (factor A)	Micronutrient fertilizer (factor C)	Fruit harvesting standard (factor D)			Mean for factor D
		SS	LS	TR	
Kibria F1	control – water treatment	26,446	32,634	38,811	32,630
	Rostok Cucumber	28,539	35,780	44,097	36,139
	Quantum PLATINUM	30,429	38,189	48,796	39,138
	Mean for factor C	28,475	35,535	43,896	35,969
Madeira F1	control – water treatment	31,006	36,893	43,903	37,267
	Rostok Cucumber	33,367	40,067	48,753	40,729
	Quantum PLATINUM	35,069	43,114	53,394	43,859
	Mean for factor C	33,141	40,018	48,677	40,612

Note: marginal means for factor C are given in bold. Compiled from field experiment data. LSD_{05} (range for 2023–2025), t/ha: A – 1,08–1,58; C – 0,83–1,35; D – 1,66–1,91; AC – 1,32–1,74; CD – 2,05–2,47; AD – 1,50–1,91; ACD – 2,33–2,58.

By individual marketable standard (ACD interaction, upper limit of LSD_{05} = 2,58 t/ha), the advantage of Quantum PLATINUM over the control was significant in all fractions of both hybrids (3,98–9,99 t/ha). Its advantage over Rostok Cucumber was significant in the TR fraction of both hybrids (4,64–4,70 t/ha) and in the LS fraction of Madeira F1 (3,05 t/ha), but did not exceed LSD_{05} in the SS fraction (1,70–1,89 t/ha) or in the LS fraction of Kibria F1 (2,41 t/ha). The largest absolute increment from Quantum PLATINUM was obtained in the TR fraction (9,49–9,99 t/ha), which is consistent with the role of trace elements in sustaining the prolonged filling of large fruit [17, 20, 29].

Comparison of the three-year means (Table 7) showed a predominantly additive action of the factors, with a synergistic component at the highest level of intensification.

In Kibria F1, the increments from Organic-Balance alone and Quantum PLATINUM alone were 3,37 and 5,69 t/ha (sum 9,06 t/ha), whereas their combination gave 10,91 t/ha; in Madeira F1 the corresponding values were 4,01 and 5,96 t/ha (sum 9,97 t/ha) against 11,62 t/ha. The excess of the combined effect over the sum of the individual effects (1,65–1,85 t/ha) is consistent with the concept of mutual enhancement between rhizosphere microorganisms and chelated trace elements [2, 13, 28]; its statistical significance should be verified in further research.

Summarizing the statistical evaluation, the significance of the effects of hybrid, biopreparations and micronutrient fertilizers at the level of main effects was confirmed in all cases for which LSD_{05} was calculated. Differences between adjacent factor levels in the SS fraction mostly lay within the experimental error, whereas in the LS and TR

fractions they were significant. Thus, as fruit mass increases, not only the absolute response of the crop to biological and micronutrient support increases, but also the reliability with which this response can be detected in a field experiment. A detailed analysis of all 18 factor

combinations over the three-year period (Table 7) confirms the stability of the established regularities at the level of each individual combination of factors, and not only of the extreme treatments.

7. Mean yield of cucumber fruit across the three marketable standards (SS, LS, TR) depending on the hybrid, biopreparation and micronutrient fertilizer (mean for 2023–2025), t/ha

Hybrid (factor A)	Biopreparation (factor B)	Micronutrient fertilizer (factor C)			Mean for factor C
		control – water treatment	Rostok Cucumber	Quantum PLATINUM	
Kibria F1	control – water treatment	30,850	33,983	36,535	33,786
	Azotofit	32,821	36,011	39,128	35,982
	Organic-Balance	34,223	38,420	41,757	38,130
	Mean for factor B	32,630	36,139	39,138	35,969
Madeira F1	control – water treatment	35,175	38,501	41,136	38,267
	Azotofit	37,450	40,311	43,650	40,550
	Organic-Balance	39,181	43,125	46,792	43,026
	Mean for factor B	37,267	40,729	43,859	40,612

Note: mean (marginal) values for factor B are given in bold. Compiled from field-experiment results, 2023–2025.

Within hybrid Kibria F1, the mean yield across the marketable standards increased from 30,850 t/ha (full control) to 41,757 t/ha (Organic-Balance + Quantum PLATINUM; +35,4 %), and within hybrid Madeira F1 – from 35,175 to 46,792 t/ha (+33,0 %). In none of the 18 factor combinations was the general ranking (Madeira F1 > Kibria F1; Organic-Balance > Azotofit > control; Quantum

PLATINUM > Rostok Cucumber > control) violated, which indicates the absence of antagonistic interaction between the factors and allows the combination of preparations to be regarded as effective for both hybrids. The dynamics of the mean yield by year (Table 8, Fig. 1) quantitatively reflect the scale of the influence of abiotic stress on the production process of the crop.

8. Dynamics of the mean yield of cucumber fruit across the three marketable standards (SS, LS, TR) by years and hybrids

Year / indicator	Kibria F1, t/ha	Madeira F1, t/ha	Difference M–K, t/ha (%)	HTC of growing season
2023 (favourable)	46,45	51,00	+4,55 (9,8 %)	0,48–0,52
2024 (extreme drought)	29,99	34,55	+4,56 (15,2 %)	0,25–0,28
2025 (moderate drought)	31,48	36,28	+4,80 (15,2 %)	0,32–0,38
2023–2025 (mean)	35,97	40,61	+4,64 (12,9 %)	–

Note: mean values across the three marketable standards; compiled from field-experiment results, 2023–2025.

On average over the three years, the mean yield across the marketable standards ranged from 30,850 t/ha (Kibria F1, absolute control) to 46,792 t/ha (Madeira F1 + Organic-Balance + Quantum PLATINUM) – an increment of 51,7 % relative to the control. The absolute advantage of hybrid Madeira F1 over hybrid Kibria F1 remained practically

unchanged from year to year (+4,55...+4,80 t/ha), whereas its relative expression increased in dry years – from 9,8 % in the favourable year 2023 to 15,2 % in 2024–2025 – which characterizes the higher ecological plasticity and heat tolerance of hybrid Madeira F1 [15, 30].

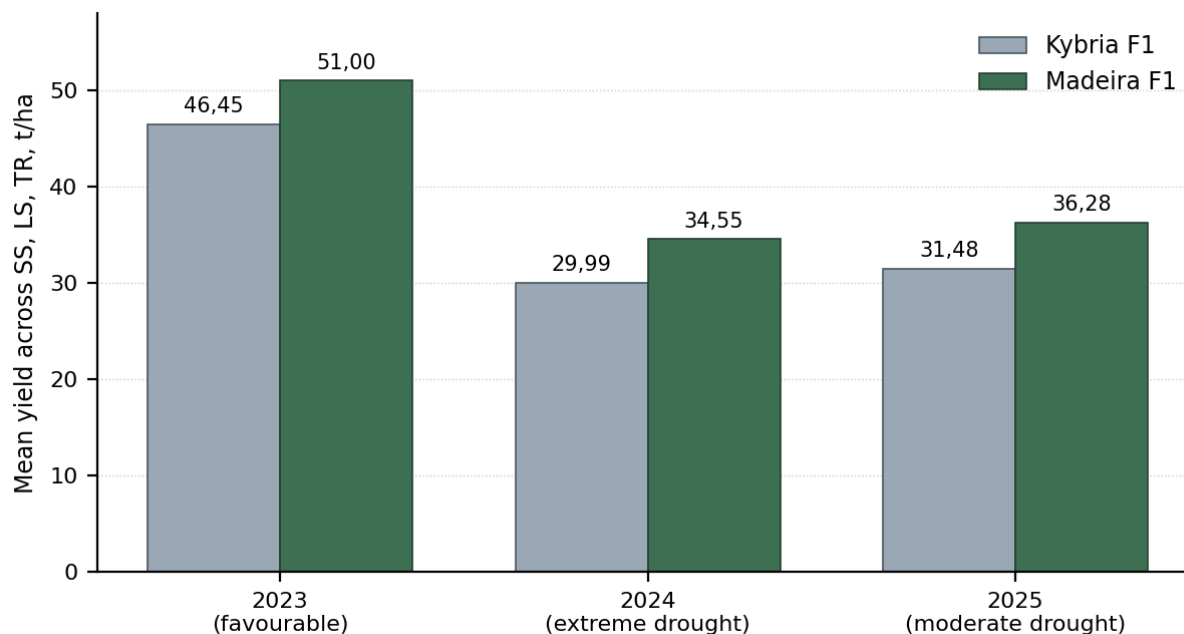


Fig. 1. Dynamics of the mean yield of cucumber fruit across the three marketable standards (SS, LS, TR) by years and hybrids, t/ha

The results obtained have practical significance. Within a single hybrid, the transition from the absolute control to the combined application of Organic-Balance and Quantum PLATINUM increased the piculi yield in 2023 by 18,5–20,8 % and the three-year mean yield across the marketable standards by 33,0–35,4 %, and the effect of the preparations was retained under the extreme drought of 2024, when the risk of yield shortfall is greatest. Thus, the application of biopreparations and chelated trace elements by fertigation should be regarded not only as a means of intensifying the production process, but also as an element of adaptive technology that increases the resilience of cucumber production to the climatic risks of the Southern Steppe of Ukraine [16, 23, 26]. The results obtained generally agree with the data of international studies on the effectiveness of rhizosphere biopreparations and micronutrient fertilizers on cucumber [13, 24, 28]; the increments from micronutrient fertilizers in our experiment (17,7–19,9 % on average over three years) are comparable to those obtained in foreign trials [17, 27, 29]. The soil of the experimental plot has a neutral reaction (pH 6,8–7,2), under which the availability of

trace elements is not strongly limited by soil pH [18, 25]. Therefore, the response of cucumber to micronutrient fertilizers can more likely be attributed to the high demand of intensively fruiting hybrids for trace elements under irrigation and to the reduced activity of root uptake under heat stress. The application of chelated trace elements by fertigation directly into the zone of the most active roots, together with the stimulation of root growth by rhizosphere bacteria, may improve their uptake under these conditions [13, 25, 20]. Since the content of mobile forms of Zn, Mn and B and of carbonates in the soil was not determined in this study, these explanations should be regarded as hypotheses that require verification by soil and plant analysis.

The revealed differentiation of the response of the marketable fractions to the studied factors (the highest sensitivity of SS, the greatest absolute response of TR) supplements existing notions of the formation of cucumber productivity [30, 32] with new empirical data obtained using a system of marketable standards rather than only total yield. This is also relevant for the practice of hybrid selection: genotypes intended for the production of small-fruited produce (piculi,

gherkins) require increased attention to adaptability factors at the early phases of generative development, whereas for hybrids of table use (greens) the priority is ensuring prolonged and stable mineral nutrition.

The data obtained also agree with the conclusions on the role of drip irrigation as a necessary but insufficient condition for the sustainable productivity of cucumber in arid regions [16, 23, 26]: despite the identical irrigation regime in all treatments of the experiment, the difference between the extreme technological combinations exceeded 50 %, which confirms the important role of the biological and micronutrient support of the crop in realizing the productive potential of cucumber hybrids under conditions where the soil water deficit is eliminated by irrigation, while the temperature regime and the balance of mineral nutrition remain the limiting factors.

A limitation of the study is that the results were obtained within a single soil-and-climate micro-region and with a single method of irrigation (drip), and fruit quality indicators and the micronutrient status of the soil and plants were not determined; therefore, the stability of the established regularities requires further verification under other soil conditions, irrigation systems (sprinkling, subsurface drip) and protected-ground conditions. Promising directions for further research are the evaluation of fruit quality (dry matter, sugars, nitrates, share of non-standard fruit), the determination of the mobile forms of trace elements in the soil and their content in plants, as well as an economic, energy and ecological assessment of the revealed technological combinations for each marketable standard.

Conclusions

1. The fruit yield of cucumber hybrids under drip irrigation in the conditions of the Southern Steppe of Ukraine was determined by the combined influence of the hydrothermal regime of the year, the hybrid genotype, the biopreparation and the micronutrient fertilizer. The contrast of the weather conditions of 2023–2025 (HTC from 0,25–0,28 in 2024 to 0,48–0,52 in 2023) caused the mean yield across the marketable standards to fluctuate

from 29,99–34,55 t/ha (2024) to 46,45–51,00 t/ha (2023).

2. For all three fruit harvesting standards – piculi (SS), gherkins (LS) and greens (TR) – hybrid Madeira F1 exceeded Kibria F1 in yield in all study years, on average by 4,64 t/ha, or 12,9 %; the difference was significant in all cases for which LSD_{05} was calculated. The relative advantage of the hybrid increased in dry years (from 9,8 to 15,2 %), which indicates its higher drought and heat tolerance.

3. Of the studied biopreparations, Organic-Balance was the most effective: on average over three years it increased yield by 12,4–12,9 % relative to the control, and within each hybrid its advantage over Azotofit (2,15–2,48 t/ha) was significant. Of the micronutrient fertilizers, Quantum PLATINUM provided the largest increments (17,7–19,9 %); its advantage over Rostok Cucumber was significant for the three-year means within each hybrid (3,00–3,13 t/ha) and in the TR fraction, but not in the SS fraction. The combined effect of Organic-Balance and Quantum PLATINUM exceeded the sum of their individual effects by 1,65–1,85 t/ha.

4. The early, small-fruited SS fraction proved most sensitive to drought (yield reduction in 2024 by 29,2–37,9 %), whereas the TR fraction formed the highest yield and the largest absolute response to the biopreparations (in 2023 the difference between Organic-Balance and the control was 7,9–9,3 t/ha against 3,1–3,4 t/ha in SS). The LS fraction occupied an intermediate position by both criteria.

5. The highest productivity, regardless of the year, was formed in the treatment hybrid Madeira F1 + Organic-Balance + Quantum PLATINUM applied by fertigation, which on average over the three years provided an increment of mean fruit yield of 51,7 % relative to the absolute control. This combination is expedient to recommend as the basis of an adaptive technology for cucumber cultivation under drip irrigation in the conditions of the Southern Steppe of Ukraine.

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