



Cultivar - Specific Biostimulant Application Enhances Heat Stress Tolerance and Pest Resistance in Potato (*Solanum tuberosum*) under Semi - Arid Conditions

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ABSTRACT

Heat stress caused by climate change makes it hard to grow potatoes in semi-arid areas, and it also makes pests more of a problem. This study examined the cultivar-specific responses of two *Solanum tuberosum* cultivars to a foliar VIGORIZER biostimulant (25% *Ascochyllum nodosum*, 0.5% glycine betaine, 0.05% Fe-EDDHA) under field circumstances in Nineveh, Iraq, where temperatures above 28 °C during tuberization. A split-plot randomized complete block design examined a heat-sensitive cultivar ('Riviera') and a heat-tolerant cultivar ('Arizona') with and without the management of a biostimulant. There were big differences between genotypes. Using biostimulants made 'Riviera' plants perform much better. The tuber weight increased from 192 to 385 g plant⁻¹, the total yield was from 0.49 to 0.82 kg plant⁻¹, the SPAD chlorophyll index went up by 4.4 units, and the tuber crude protein went up by 46%. The Colorado potato beetle (*Leptinotarsa decemlineata*) caused 57% less damage to the leaves of treated "Riviera" plants. "Arizona" showed slight but important gains in yield and nutritional levels. Physiological and nutrient analyses connected the improvements in "Riviera" to better nitrogen uptake (leaf N went from 2.94% to 3.48%) and more stable photosystem II. A notable cultivar × treatment interaction ($\eta^2 = 0.74$) demonstrates that biostimulant efficacy is contingent upon genotype. These results show that applying foliar biostimulants to certain areas can help plants deal with heat stress and make them stronger and more resistant to pests in potato varieties that are prone to them.

تعزيز تحمل الإجهاد الحراري ومقاومة الآفات في البطاطا (*Solanum tuberosum*) تحت الظروف شبه الجافة من خلال تطبيق محفزات حيوية خاصة بالصنف

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الخلاصة

يشكل الإجهاد الحراري الناجم عن التغير المناخي تحديات كبيرة لإنتاج البطاطا في المناطق شبه الجافة، وغالبًا ما يؤدي إلى تفاقم ضغط الآفات. قُيِّمت هذه الدراسة الاستجابات الخاصة بالصنف لاثنتين من أصناف *Solanum tuberosum* لتطبيق محفز حيوي ورقي من نوع VIGORIZER (25% *Ascochyta nodosa*)، و0.5% غلايسين-بيتين، و0.05% حديد EDDHA تحت ظروف حقلية في نينوى، العراق، حيث تجاوزت درجات الحرارة 28°C خلال مرحلة تكوين الدرنات. أُستخدم تصميم القطاعات الكاملة المعشاة المنشقة لمقارنة صنف حساس للحرارة (Riviera) وصنف متحمل للحرارة (Arizona) مع وبدون تطبيق المحفز الحيوي. أشارت النتائج إلى وجود فرق وراثي معنوي. إذ حسّن تطبيق المحفز الحيوي أداء صنف Riviera بشكل ملحوظ، مما أدى إلى زيادة بنسبة 101% في وزن الدرنات (من 192 إلى 385 غم نبات⁻¹)، وزيادة بنسبة 67% في الحاصل الكلي (من 0.49 إلى 0.82 كغم نبات⁻¹)، وتحسّن معنوي في دليل الكلوروفيل SPAD (+4.4 وحدات)، وزيادة بنسبة 46% في محتوى البروتين الخام للدرنات. علاوة على ذلك، أظهرت نباتات Riviera المعاملة انخفاضًا بنسبة 57% في الضرر البصري الناتج عن خنفساء البطاطا الكولورادية (*Leptinotarsa decemlineata*) (درجة 1.8 مقابل 4.2 على مقياس 0-5) مقارنة بمعاملة المقارنة. ولوحظت مقاومة مشابهة، وإن كانت أقل وضوحًا، في نباتات Arizona-Vigorizer. أظهر صنف Arizona استجابة أكثر تواضعًا لكنها معنوية في مؤشرات الحاصل والعناصر الغذائية. وربطت التحليلات الفسيولوجية والغذائية مكاسب صنف Riviera بتحسّن تمثيل النيتروجين (زيادة نيتروجين الأوراق من 2.94% إلى 3.48%) واستقرار النظام الضوئي الثاني. ويُظهر الارتباط المعنوي بين الصنف والمعاملة ($\eta^2 = 0.74$) أن فاعلية المحفزات الحيوية تعتمد على الخلفية الوراثية. وتبيّن هذه النتائج أن التطبيق الورقي الموجّه للمحفزات الحيوية يمكن أن يخفف في الوقت نفسه من آثار الإجهاد الحراري ويعزز قوة النبات لتحسين مقاومة الآفات في الأصناف الحساسة، مما يوفر إستراتيجية مستدامة لتعزيز القدرة على التكيف مع المناخ في نظم إنتاج البطاطا.

الكلمات المفتاحية: *Solanum tuberosum* ، محفز حيوي ، المقاومة المستحثّة ، *Leptinotarsa decemlineata*.

INTRODUCTION

The potato (*Solanum tuberosum* L.) is the heart of world food security and thus stands as the fourth most important food crop with a yearly production of over 376 million tons (FAO, 2023). This is not only a matter of quantity but also that potatoes alongside their production exist in terms of nutritional quality; they contain almost all essential vitamins, minerals, and carbohydrate. They are extremely versatile, growing in all sorts of climates, hence being a lifeline for feeding increasing numbers of people (Devaux *et al.*, 2021). Yet here come the challenges with climate change; it is the most daunting issue for potato yields, especially in Iraq's hot and dry regions. When tuberization temperatures rise above the adjacent optimum, usually above 28 °C during essential growth stages, this has become difficult for a potato plant (Hameed *et al.*, 2018; Mulders *et al.*, 2024). The tubers are just not able to initiate, grow, and adequately translocate nutrients due to the heat; hence yield reductions of as high as 30 to 50% are being reported (Obiero *et al.*, 2019).

Heat stress disrupts potato growth and development through multiple pathways. High-temperature variation disturbs photosynthesis and reduces chlorophyll production that can in fact be seen as low SPAD values (Tang *et al.*, 2018). Increased heat stress triggers oxidative damage- reactive oxygen species (ROS) accumulation, leaf senescence, and plasma membrane leakage (Hancock *et al.*, 2013). This is severe for fast-growing temperate varieties, such as "Riviera", because they do not possess the intrinsic heat tolerance which is found in the specially bred varieties such as "Arizona" (Gautam *et al.*, 2024). Local climate models in fact indicate 2-4 °C warming over Mediterranean and semi-arid regions by the year 2050 (Bongaarts, 2024). Therefore, it becomes an urgent requirement to seek mechanisms to assist potatoes in coping with heat stress.

Here, biostimulants step in. This is a new generation of agrochemicals with an aim to enhance crop resilience to stresses. The biostimulant mixtures that are currently in use typically consist of seaweed extracts (e.g., *Ascophyllum nodosum*), glycine-betaine, and micronutrient chelates (e.g., Fe-EDDHA). They provide several mechanisms of action, including activating plant defense systems, regulating plant water balance, and increasing nutrient-use efficiency (Rouphael & Colla, 2020; Xu & Leskovar, 2015). For example, seaweed extracts are rich in cytokinins, betaines, and polysaccharides that stabilize the photosynthetic proteins and activate antioxidant enzymes, enhancing heat tolerance (Shukla *et al.*, 2019). Glycine-betaine, however, is the most active osmoprotectant. It protects cells as well as enzymes from any heat-induced damage (Annunziata *et al.*, 2019).

And there is more biostimulants that do not only deal with heat and drought. Evidence is increasing that they help plants to resist insect pests. A healthy, resilient plant will engage its defenses, rendering itself less inviting to insects (Parađiković *et al.*, 2011). This bears great importance as potato crops have always been threatened by the Colorado potato beetle (*Leptinotarsa decemlineata*), a notorious pest that can wipe out entire fields (Alyokhin *et al.*, 2014). Biostimulants have been shown to balance plant nutrient status, especially potassium and nitrogen, while strengthening both physical and chemical barriers against insect assaults (Canellas and Olivares, 2014; Rouphael and Colla, 2020). Though not insecticides, by promoting resistance in the crop, biostimulants readily fit into an integrated pest management (IPM) program.

A vast amount is still unknown concerning potatoes and biostimulants. A large part of research conducted luminaries on the biostimulants show that it was mostly greenhouse or laboratory-based and not field-based, especially not in real ambient, heat-stressed places (Rouphael & Colla, 2020). A huge gap would entail the disregard with which scientists treat the response of different potato varieties to treatments considering that we already know that heat tolerance varies considerably from variety to variety (Rakkammal *et al.*, 2022). Therefore, a one-size-fits-all approach cannot apply. Furthermore, determining the best application procedures such as timing, growth stage, and frequency for hot and dry environments in potato-growing regions remains another concern (Kong *et al.*, 2024; Nzaramba *et al.*, 2013).

This study was designed to address these critical knowledge gaps through comprehensive field trials conducted in Iraq's Nineveh Governorate. We specifically evaluate: (1) the cultivar - dependent yield and physiological responses of a heat - sensitive ('Riviera') and a heat - tolerant ('Arizona') potato variety to a multi - component VIGORIZER biostimulant; (2) the associated changes in nutrient uptake efficiency and tuber quality as potential mechanisms for enhanced stress tolerance; and (3) the concurrent effect on plant vigor and resistance to Colorado potato beetle. This research intends to provide a sound scientific basis for the development of practical application guidelines for potato production systems in semi-arid environments and thus strategy advanced climate-smart solutions towards achieving sustainable agriculture in line with global food security objectives.

MATERIALS AND METHODS

Experimental Site and Soil Characteristics

The experiment was carried out at Qarakoyun Agricultural Research Station, Nineveh Governorate, Iraq, during the spring season of the year 2025 growing for crops. The station coordinates are 36°21'N, 43°07'E, and 230 m above sea level. The texture of the soil was clay loam and was a Typic Calcixerept. The top 30 cm profile before planting had a pH of 7.8 ± 0.1 , moderate salinity measured ($EC_e = 1.2 \pm 0.1$ dS m⁻¹), and an organic carbon content of 9.3 ± 0.7 g kg⁻¹. Table 1 (Kalaji *et al.*, 2017) indicates that the most important soil fertility factors were present nitrogen (22 mg kg⁻¹), Olsen phosphorus (11 mg kg⁻¹), and exchangeable potassium (185 mg kg⁻¹).

Table 1: Pre - planting physio - chemical characteristics of the experimental soil (0 – 30 cm), Qarakoyun Research Station, Nineveh Governorate, Iraq, February 2025.

Parameter (Unit)	Mean $\pm$ SD
Texture	Clay loam
pH (1:1 H ₂ O)	7.8 ± 0.1
EC_e (dS m ⁻¹)	1.2 ± 0.1
Organic Carbon (g kg ⁻¹)	9.3 ± 0.7
Total N (g kg ⁻¹)	1.0 ± 0.1
Olsen-P (mg kg ⁻¹)	11 ± 2
Exchangeable K (mg kg ⁻¹)	185 ± 12
CaCO ₃ Equivalent (%)	38 ± 3
CEC (cmol _c kg ⁻¹)	15.4 ± 1.2
Bulk Density (Mg m ⁻³)	1.33 ± 0.05
Field Capacity (% w/w)	19.6 ± 1.1
Wilting Point (% w/w)	7.9 ± 0.5

Experimental Design and Treatments

The experiment followed a split - plot randomized complete block design (RCBD) with four replications. The main plot featured two potato cultivars: ' Riviera ', suited to temperate conditions, and ' Arizona ', known for its heat tolerance. Within each main plot, sub - plots were either treated with VIGORIZER — a biostimulant from Cosmocel S. A. (Santiago, Chile) containing 25 % Ascophyllum nodosum extract, 0.5 % glycine - betaine, and 0.05 % Fe - EDDHA — applied at a rate of 2.5 L per hectare or left as untreated controls sprayed with water. Certified Generation 2 seed tubers (45 – 55 mm) were obtained from Nahar Alawrad Agricultural Company (Erbil, Iraq; <https://naharalawrad.iq>) and planted on 15 February 2025 in 20 m² field plots.

Crop Management Practices

All plots received uniform basal fertilization (120 kg N ha⁻¹ as urea, 90 kg P₂O₅ ha⁻¹ as triple superphosphate, and 100 kg K₂O ha⁻¹ as potassium sulfate). Drip irrigation - maintained soil moisture at - 30 kPa, monitored using tensiometers (Model R, Irrometer Company, Riverside, CA, USA). VIGORIZER was applied as a foliar spray at 30, 45, and 60 days after emergence (DAE) using a CO₂ - pressurized backpack sprayer (Model CP3, Bellspray Inc., Opelousas, LA, USA) calibrated to deliver 400 L ha⁻¹. No insecticides

were applied during the growing season to allow for natural Colorado potato beetle infestation and assessment.

Data Collection and Measurements

Yield Components

At 95 days after emergence (DAE), tubers from a 3 m² plot area were harvested, manually cleaned, and weighed on a precision balance (KERN & Sohn GmbH, Model EW 220 - 3NM, Germany). Plant height was measured from the base to the apex using a ruler with millimeter graduations.

Physiological Measurements

Chlorophyll content was assessed between 09: 00 - 11: 00 h on the fourth fully expanded leaf using a SPAD - 502Plus chlorophyll meter (Konica Minolta Sensing, Inc., Osaka, Japan) following the protocol of (Kalaji *et al.*, 2017).

Biotic Stress Assessment: Colorado Potato Beetle (CPB) Damage

Damage from Colorado potato beetle (*Leptinotarsa decemlineata*) was assessed weekly from 40 DAE until harvest. CPB pressure was natural and uniform across the experimental site. Defoliation damage was visually scored on a 0 to 5 scale adapted from Zehnder *et al.* (2007) on ten randomly selected plants per plot:

0 = No damage: No feeding injury observed.

1 = Minor damage: < 5 % of leaf area consumed.

2 = Slight damage: 5 – 15 % of leaf area consumed.

3 = Moderate damage: 16 – 35 % of leaf area consumed.

4 = Severe damage: 36 – 75 % of leaf area consumed.

5 = Major damage: > 75 % of leaf area consumed or complete defoliation.

The average score per plot was used for analysis. A lower score indicates higher resistance or tolerance to CPB feeding.

Nutrient Analysis

Leaf and tuber samples were oven - dried at 65 ° C for 72 h (Model UF 110, Memmert GmbH, Schwabach, Germany), then ground (Model ZM 200, Retsch GmbH, Haan, Germany) and sieved to 0.5 mm. Total nitrogen was determined via Kjeldahl digestion (Model VAPODEST 450, Gerhardt GmbH, Königswinter, Germany), phosphorus by molybdate - vanadate colorimetry (UV - 1800 spectrophotometer, Shimadzu Corporation, Kyoto, Japan), and potassium by flame photometry (Model 410, Sherwood Scientific Ltd., Cambridge, UK). Crude protein was calculated as total N × 6.25 (Mariotti *et al.*, 2008).

Statistical Analysis

Data were analyzed using a split - plot analysis of variance (ANOVA) in Statistix 10 software. The model tested the effects of cultivar (main plot), biostimulant treatment (sub - plot), and their interaction. For the Colorado potato beetle damage score (ordinal data), the non - parametric Aligned Rank Transform (ART) procedure was applied before ANOVA. Treatment means were separated using Duncan 's Multiple Range Test (DMRT) at a 5 % significance level ($p \leq 0.05$). Data are presented as mean $\pm$ standard deviation (SD).

RESULT AND DISCUSSION

The VIGORIZER biostimulant produced significant effect yields but varied according to the cultivar used in this semi-arid, heat-stressed conditions study (Table 2). Again, treatment was very rewarding for the temperate cultivar "Riviera." There was a dramatic increase in tuber weight per plant by 101% of increase from 192 g to 385 g, resulting in total yield increasing by 67%, with contributions from 0.49 kg plant⁻¹ to 0.82 kg plant⁻¹. However, among the heat-adapted cultivar, "Arizona" did not seem to have much of a problem with this. Tubers grew heavier with an increased total yield to 90 and 40 percent, respectively, but were still less than that of "Riviera" treated. There was very strong Cultivar x Treatment (C x T) interaction ($p < 0.001$; $\eta^2 = 0.74$), indicating that the effect of the biostimulant is associated with the genetic constitution of the potato variety.

There are varieties where yield components respond differently to the use of biostimulants. VIGORIZER biostimulant had a pronounced impact on evaluating the currently studied yield components, although the amount of effect depended on the cultivar used in this semi-arid, heat-stressed conditions study (Table 2). After some treatments, big yield increases were noted by the temperate cultivar "Riviera." There was an increase of tuber weight per plant into 385 g from 192 g, an increase of 101% or a total weight yield increase of 67%, from 0.49 kg plant⁻¹ to 0.82 kg plant⁻¹. On the other hand, heat-adapted "Arizona" seemed to react not as badly. Tubers and total yield increased by 90% and 40% respectively, but lower than those of the treated "Riviera." The strong Cultivar x Treatment (C x T) interaction ($p < 0.001$; $\eta^2 = 0.74$) reveals the biostimulant's import can be attributed directly to the genetic make-up of the potato variety..

The VIGORIZER biostimulant had a big effect on yield metrics when used in semi-arid, heat-stressed conditions, but the effect depended on the cultivar used in this study (Table 2). After treatment, the temperate cultivar 'Riviera' showed a big and important rise in yield. The total output went up by 67%, from 0.49 kg per plant to 0.82 kg per plant. The weight of the tubers per plant went up by 101%, from 192 g to 385 g. The heat-adapted variety "Arizona," on the other hand, only got a little better, with tuber weight and total yield going up by 90% and 40%, respectively, but still not as much as the treated "Riviera." The significant Cultivar $\times$ Treatment (C $\times$ T) interaction ($p < 0.001$; $\eta^2 = 0.74$) shows that the potato variety's genetic makeup is closely related to how well the biostimulant works..

Several responses can be explained by the basic stress adaptation methods of the two cultivars. "Riviera," a genotype from a cooler climate, probably has stress-response pathways that can be turned on by the ingredients in VIGORIZER. The glycine-betaine component may stimulate the development of betaine-aldehyde dehydrogenase (BADH), a crucial enzyme for stress tolerance, a mechanism that is less noticeable in cultivars that have already acclimated, such as 'Arizona' (Aksoy *et al.*, 2015; Nahar *et al.*, 2015). The seaweed extract in the biostimulant also has cytokinins and other compounds that turn on cell expansion genes like EXPA1 and EXPA4. These genes are very important for tuber bulking, especially when the environment is not ideal (De Saeger *et al.* 2020; Jayaweera *et al.* 2024). 'Arizona' appears to be close to its physiological ceiling under these conditions.

Table 2: The Effect of Biostimulant (Vigorizer) on Yield Components and Physiological Traits of Two Potato Varieties (Riviera and Arizona)

Parameter	Riviera- Control	Riviera- Vigorizer	Arizona- Control	Arizona- Vigorizer	F- Value (C×T)	P- Value	H ²
Tuber Weight (G Plant ⁻¹)	192 ± 68 ^b	385 ± 96 ^a	118 ± 15 ^c	224 ± 18 ^c	28.9	<0.001	0.74
Total Yield (Kg Plant ⁻¹)	0.49 ± 0.08 ^c	0.82 ± 0.11 ^b	0.40 ± 0.12 ^a	0.56 ± 0.15 ^a	9.8	0.003	0.42
Spad Index	46.4 ± 3.9 ^b	50.8 ± 4.3 ^a	46.1 ± 3.5 ^b	48.3 ± 3.7 ^{ab}	3.9	0.013	0.11

Values are expressed as mean ± standard deviation (SD). Distinct lowercase letters in a row signify statistically significant differences as determined by Duncan's test ($p < 0.05$). The F-statistic, P-values, and η^2 for the C × T interaction are presented. Symbols *, **, and *** indicate significance levels at $p < 0.05$, 0.01, and 0.001, respectively.

Biostimulant application significantly improved the physiological state of both varieties, though to different degrees (Table 3). The SPAD index went up considerably in "Riviera" (from 46.4% to 50.8%) and a positive, though not very strong, trend was observed for "Arizona" (from 46.1% to 48.3%) with respect to chlorophyll in the leaves. The increase in the potential of the plants for photosynthesis is vital during a hot period, since heat stress would denature chlorophyll and damage photosystem II (PSII). VIGORIZER contains glycine-betaine that stabilizes PSII and eliminates reactive oxygen species. This allows the plants to remain green and produce food (Hancock *et al.*, 2013; Liu *et al.*, 2022). A 4.4 unit increase in "Riviera" is of extreme agronomic importance because Li *et al.* (2023) correlated each 1-unit SPAD increase in late-season potatoes with an additional 0.4 t ha⁻¹ yield.

Another critical and novel observation was that plants better deterred the Colorado potato bug (*Leptinotarsa decemlineata*). The stressed "Riviera-Control" plants, and both "Arizona" treatments, experienced more beetle damage and leaf loss compared to "Riviera-Vigorizer" plants. Probably the reason for this protection is that plants become strong and receive sufficient nutrients. Healthy and unstressed plants can use secondary metabolites and proteins for better defense against biotic factors (Shukla *et al.*, 2021). Exceedingly high consumption of nutrients, particularly nitrogen and potassium, can enhance plants' resistance to herbivory (Amtmann *et al.*, 2008). The important change was in "Riviera" (from 46.4% to 50.8%) and very little change in "Arizona" (from 46.1% to 48.3%). The SPAD index tells how much chlorophyll is in leaves. Considerably, plants need to make more food under photosynthesis during hot weather because heat stress damages chlorophyll and PS II. It is known that glycine-betaine in VIGORIZER will stabilize PS II to contribute to eliminating reactive oxygen species. This helps the plants maintain their green color and grow more food (Hancock *et al.*, 2013; Liu *et al.*, 2022). In a similar way the ' Arizona - Vigorizer ' plants showed marginally less damage when compared to ' Arizona - Control ', suggesting a mild biostimulant-mediated priming of defense mechanisms even in a more resistant variety.

Table 3: Physiological Traits and Biotic Stress Observations of Two Potato Varieties as Influenced by Biostimulant Application

Parameter/Observation	Riviera- Control	Riviera- Vigorizer	Arizona- Control	Arizona- Vigorizer	F- Value (C×T)	P- Value	H ²
Spad Index	46.4 ± 3.9 ^b	50.8 ± 4.3 ^a	46.1 ± 3.5 ^b	48.3 ± 3.7 ^{ab}	3.9	0.013	0.11
Visual Damage Rating (0-5) ¹	4.2 (High)	1.8 (Low)	2.5 (Moderate)	2.0 (Low- Moderate)	-	-	-

Significant differences between treatments are denoted by different lowercase letters (Duncan's test, $p < 0.05$).

The VIGORIZER application raised the levels of macronutrients in both cultivars, however, "Riviera" was influenced more (see Table 4). In "Riviera," the nitrogen in the leaves went up by 18%, the phosphorus by 56%, and the potassium by 33%. "Arizona" also got better, especially its potassium levels, but not as much. This biostimulant works in a way that makes sense: it helps plants take in more nutrients. Scientists have found that some amino acids and seaweed extracts can turn on genes in roots that move nutrients like nitrate and phosphate around (González-Morales *et al.*, 2021). Adding chelated iron (Fe-EDDHA) probably made things even worse by turning on enzymes that help plants get more nitrogen (Briat *et al.*, 2015; Kim & Lee, 2019). "Riviera" worked better because its roots and metabolism are more in tune with this kind of boost, so it took in and moved nutrients more efficiently.

Table 4: The effect of biostimulant application on the nutrient content of the leaves of two potato varieties

Parameter Leaf Nutrients (%)	Riviera- Control	Riviera- Vigorizer	Arizona- Control	Arizona- Vigorizer	F- Value (C×T)	P- Value	H ²
Nitrogen	2.94 ± 0.12 ^b	3.48 ± 0.14 ^a	2.88 ± 0.11 ^b	3.15 ± 0.13 ^{ab}	6.2*	0.038	0.21
Phosphorus	0.36 ± 0.02 ^b	0.56 ± 0.03 ^a	0.34 ± 0.02 ^b	0.42 ± 0.02 ^{ab}	4.1	0.077	0.14
Potassium	3.31 ± 0.15 ^b	4.40 ± 0.20 ^a	3.15 ± 0.14 ^b	3.84 ± 0.18 ^{ab}	7.3**	0.027	0.25
Crude Protein	18.38 ± 0.72 ^b	21.75 ± 0.88 ^a	18.00 ± 0.69 ^b	19.69 ± 0.81 ^{ab}	5.9*	0.041	0.20

* Note: Mean values ± standard deviation are represented in the data. Significant differences are indicated by different lowercase superscript letters within a row (Duncan's test, $p < 0.05$). C × T: Cultivar × Treatment interaction; *, ** indicate significance at the probability levels of 0.05 and 0.01, respectively.

In addition to being more aesthetically pleasing, healthier leaves increased the nutritional value of the tubers (see Table 5). Crude protein in "Riviera" increased by 46%, from 9.19% to 13.44%, the largest change. The harvest will have a much higher food value as a result. Even "Arizona," which had a higher initial protein intake, was able to achieve

a strong 16% rise. Why is this happening? Nitrogen was transported from the leaves by the plants and packed into the tubers. Not only did the biostimulant help the plants absorb more nutrients, but it also facilitated their movement and utilization of those nutrients in the tubers, which is where it matters most. When plants are under stress, this is crucial for both yield and quality (Masclaux-Daubresse *et al.*, 2010). According to Battacharyya *et al.* (2015) and Colla *et al.* (2015), these results strongly support the theory that biostimulants assist plants in directing their resources toward the parts that matter to us—the food.

Table 5: The Effect of Biostimulant Application on the Nutritional Quality of Two Potato Varieties.

Parameter Tuber Nutrients (%)	Riviera- Control		Riviera- Vigorizer		Arizona- Control		Arizona- Vigorizer		F- Value (C×T)	P- Value	H ²
Nitrogen	1.47	± 0.08 ^b	2.15	± 0.10 ^a	1.99	± 0.09 ^b	2.31	± 0.11 ^a	12.9***	0.007	0.38
Crude Protein	9.19	± 0.50 ^b	13.44	± 0.63 ^a	12.44	± 0.56 ^b	14.44	± 0.69 ^a	11.3***	0.010	0.35

* Note: The data shows mean values ± standard deviation. Differences are indicated by different lowercase (Duncan's test, $p < 0.05$). * denotes significance at the probability level of 0.001. C × T: Interaction between cultivar and treatment.

Nonetheless, the study demonstrates that the VIGORIZER biostimulant does indeed improve the capacity of potatoes to withstand heat stress and that this works well with some potato types, as for example, "Riviera." This temperate potato is appropriate for production in areas that are only somewhat dry. Increases in yield, health, nutrition, and some pest resistances are promised. The prospective increase, as inferred from SPAD readings, carries great implications for food security in regions battered by climate-related catastrophes (FAO, 2023). But for heat-adapted types such as "Arizona," not so much benefit is derived from VIGORIZER. Some minor changes can be identified in quality and energy, but nothing significant. For such people, it may be worth looking at other or combined strategies (Malik *et al.*, 2020; Mulders *et al.*, 2024).

In the future, researchers will need to establish why different cultivars react in such exceedingly different manners. Transcriptomics and isotopic labeling will probably allow for clearer elucidation (Kong *et al.*, 2024). Timing, too, is crucial: the application at the right developmental stages will prove to be a game-changer by applying VIGORIZER while tuber initiation or expansion is beginning (Nzaramba *et al.*, 2013). Therefore, the bottom line is that biostimulants are not a magical solution for every potato as this study has demonstrated. They are intuitive tools, but they work with the appropriate genotypes. Secret to cultivating a potato that withstands bad weather but remains capable of producing good long-lasting yields (Devaux *et al.*, 2021).

CONCLUSION

This study indicates that the genetic background of potato cultivars has a fundamental impact on the VIGORIZER biostimulant 's performance. Significant improvements were observed in the heat - sensitive ' Riviera ', with tuber yield doubling, photosynthetic capacity greatly increased, and tuber protein content increasing by 46 %. Crucially, Colorado potato beetle damage was reduced by 57 % in treated " Riviera " plants.

The heat - adapted ' Arizona ', on the other hand, improved pest resistance more subtly while showing only modest but noteworthy increases in yield and nutritional quality. The results show that biostimulants are more useful rather than all - purpose treatments. Though they provide less benefit to already well - adapted cultivars, their use can be an effective strategy to protect climate - sensitive cultivars from heat stress losses and simultaneously increase their resistance to pest pressure. Therefore, in semi - arid, climate - vulnerable regions, it is crucial to match certain biostimulants to compatible genotypes in order to maximize sustainable potato production.

CONFLICT OF INTEREST

The authors declare no conflicts of interest associated with this manuscript.

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