



Article

Interactive Effects of Genotype, Irrigation, and Fertilization on Physiological, Biometric, and Biochemical Traits of Runner Bean (*Phaseolus coccineus* L.)

Georgiana Rădeanu ¹, Cristina Precupeanu ¹, Gabriel-Ciprian Teliban ¹, Mihaela Roșca ¹,
José Luis Ordóñez-Díaz ², Jose Manuel Moreno-Rojas ² and Vasile Stoleru ^{1,*}

¹ Department of Horticultural Technologies, Faculty of Horticulture, “Ion Ionescu de la Brad” Iasi University of Life Sciences, 3 M. Sadoveanu Alley, 700490 Iasi, Romania; georgiana_20097@yahoo.com (G.R.); cristina_precupeanu@yahoo.com (C.P.); gabriel.teliban@iuls.ro (G.-C.T.); mihaela.rosca@iuls.ro (M.R.)

² Department of Agroindustry and Food Quality, Andalusian Institute of Agricultural and Fisheries Research and Training (IFAPA), Alameda del Obispo, Avda. Menéndez Pidal, SN, 14004 Córdoba, Spain; josel.ordonez@juntadeandalucia.es (J.L.O.-D.); josem.moreno.rojas@juntadeandalucia.es (J.M.M.-R.)

* Correspondence: vasile.stoleru@iuls.ro

Abstract

Climate change, marked by increasing temperatures and unpredictable rainfall, presents a significant challenge to the sustainable cultivation of runner beans (*Phaseolus coccineus* L.). These conditions underscore the urgent need for efficient resource management. Therefore, it is crucial to establish suitable irrigation regimes and nutritional conditions for runner bean cultivars. Furthermore, since genotype performance is strongly influenced by water availability and nutrient supply, understanding their interactive effects is essential for developing technologies that are adapted to climate change and sustain high yields of garden beans. In this context, the individual and combined effects of three runner bean cultivars (Cozia1, Cozia2, and Cozia3), two irrigation regimes (2000 and 2500 m³·ha^{−1}), and three fertilisation strategies (chemical, organic, and unfertilised) on some physiological, morphological, and biochemical parameters were assessed in this study. The field experiment was carried out in the north-eastern part of Romania over two consecutive growing seasons, following a randomized split-split plot design with three replications. The results showed that genotype had the most significant influence on the majority of traits, highlighting its dominant role over fertilization and irrigation. Under chemical fertilization and 2500 m³·ha^{−1} irrigation, Cozia2 achieved the highest grain yield (3427.60 kg·ha^{−1}) and pod number (48.13), while Cozia1 combined with chemical fertilization under 2000 m³·ha^{−1} irrigation recorded the highest total phenolic content (0.47 mg GAE·100 g^{−1} d.w.). Among cultivars, Cozia2 was highly responsive to fertilisation and irrigation variation, showing both the highest and lowest values for pod number, seed weight, and seeds per pod depending on treatment. Notably, the highest photosynthetic assimilation rates were observed in Cozia2 × IR2 × UF and Cozia3 × IR1 × OR combinations. Based on the results of this study, Cozia3 under chemical fertilization is best suited for high yields under limited water (2000 m³·ha^{−1}), while Cozia2 is best suited when chemical fertilization is combined with higher irrigation (2500 m³·ha^{−1}). However, in the context of organic cultivation, Cozia3 is identified as the most suitable cultivar.

Keywords: bean quality; cultivar performance; fertigation management; open-field crop



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1. Introduction

In recent years, legumes have transitioned from being neglected crops to becoming promising solutions for the challenges of global food security. They have garnered increasing scientific interest due to their potential contributions to sustainable agriculture, soil health, and nutrition. Research highlights the ability of legumes to fix atmospheric nitrogen, which improves soil fertility and reduces the need for synthetic fertilizers. Additionally, their diverse nutrient profiles make them essential in combating malnutrition and promoting healthier diets. For example, these plants offer a sustainable alternative to traditional animal-based proteins and are recognized for their high protein content, which ranges from 160 to 250 g per kilogram [1,2]. Furthermore, legumes are recognized for their complex phytochemical composition, rich in bioactive substances such as flavonoids, phenolic acids, and anthocyanins, compounds associated with antioxidant, antimutagenic, anticarcinogenic, and anti-inflammatory effects [3–6]. Therefore, these crops, rich in fiber, essential amino acids, vitamins, and minerals, can effectively complement primarily cereal-based diets. They contribute to dietary diversification and help reduce nutritional deficiencies, positioning legumes among the most nutritious plant-based crops available [7].

The *Phaseolus* genus includes 75 infrageneric taxa [8], with approximately 150 species [9]. Within this genus, several species are cultivated worldwide as food sources for human consumption, including *P. vulgaris*, *P. lunatus*, *P. coccineus*, *P. dumosus*, and *P. acutifolius* [10–12]. The common bean (*Phaseolus vulgaris* L.) and runner bean (*Phaseolus coccineus* L.) are often cultivated together [13], as they are closely related and capable of partial interbreed [9,14]. *Phaseolus coccineus* L. is originally from Mexico and Central America, where it is a perennial plant. However, in temperate regions, such as Romania, it behaves as an annual plant due to its sensitivity to low temperatures [15–17]. It is a herbaceous species with hypogeal emergence and cross-pollination, characterized by vigorous, twining stems (≥ 4 m) that require support. While it is widely cultivated in its native regions, in Romania it is grown on a smaller scale, primarily in home gardens, for its tender pods and dry beans [15,18,19]. Due to its nutritional value, bioactive compound content, and genetic diversity, *P. coccineus* holds considerable potential for improvement and integration into sustainable farming systems [15,17,20]. Compared to other species within the genus, it exhibits greater tolerance to low temperatures during the early growth stages [18,21]. Although it shows greater tolerance to low temperatures during the early growth stages compared to other species in its genus, it is still vulnerable to heat stress during the flowering period. High temperatures can negatively impact fertility, leading to flower abortion and reduced yields [22]. Furthermore, the beans are species with high water and nutrient demands, especially during critical growth stages such as flowering and pod filling [23,24].

Currently, due to climate change, which is marked by rising global temperatures and more frequent extreme weather events, water resources are becoming increasingly scarce and challenging to manage. This situation poses a significant challenge for bean cultivation [25,26]. Rational water use in agriculture is therefore essential, as climate projections predict increased evapotranspiration alongside reduced water availability [25]. For example, Saleh et al. [27] reported that the green bean cultivars, Bronco and Paulista, grown in an environmentally controlled greenhouse achieved the highest productivity and pod quality under the irrigation regime of 209 L m^{-2} , value representing 80% of evapotranspiration. In contrast, El-Noemani et al. [28] found that the maximum pod yield of Paulista and Bronco green beans grown in an open field in Egypt was reached with an irrigation regime of $3705 \text{ m}^3 \text{ ha}^{-1}$. This highlights that irrigation regimes can vary significantly depending on the region and growing conditions. In another study conducted in the Tarsus region of Turkey, was determined that an irrigation regime of $4280 \text{ m}^3/\text{ha}$ is adequate to achieve the highest yield of green beans in an open field [29]. Taken together,

these emphasize the importance of integrated irrigation strategies, the selection of drought-tolerant genotypes, and the use of soil moisture monitoring technologies for sustainable and resilient agricultural practices [30].

Water scarcity not only affects plant hydration but also limits the uptake of essential nutrients, thereby compromising key physiological processes such as photosynthesis. The intensity of the photosynthetic process and the resulting yield are affected by the availability of nutrients in the soil, which can be enhanced through appropriate fertilization. However, nutrient uptake is strongly dependent on adequate soil moisture, which under drought conditions can be significantly reduced [31,32]. For example, Teliban et al. [31] reported that irrigation at $3000 \text{ m}^3 \cdot \text{ha}^{-1}$ significantly increased the runner bean yield compared to unirrigated variants, regardless of the fertilization method (biosolids, chemical, microorganisms, or unfertilized). In addition to water management and genetic adaptation, proper nutrient supply is critical for optimizing the growth and yield of *Phaseolus coccineus* L. Growing beans often requires significant nitrogen application to enhance growth and yield, even though the plant can naturally fix atmospheric nitrogen through a symbiotic relationship with microorganisms [33]. It is well documented that chemical fertilizers contribute significantly to yield increases in vegetable crops, due to their high nitrogen content in a form readily assimilated by plants compared to organic fertilizers [33,34]. For instance, Teliban et al. [31] found that the yield of runner beans from chemically fertilized variants was significantly higher compared to those fertilized with biosolids, microorganisms, or left unfertilized. In contrast, Sachan and Krishna [35] reported that the highest yield of French beans was observed in the variant fertilized with poultry manure, followed by NPK and farmyard manure. Nevertheless, there is a growing trend towards the use of organic fertilizers, even in conventional farming systems. In this context, organic and microbiological fertilizers have proven to be effective, providing not only comparable production performance [36,37], but also improvements in crop quality, thus adding agricultural value [38–40].

Genotype, irrigation practices, and fertilization methods have been shown to have an impact not only on morphological and agro-productive traits but also on bean quality. For example, the studies conducted by Carbas et al. [41], Yang et al. [42], Yaneva et al. [43], García-Díaz et al. [44] and Kivu et al. [45] highlighted that genotype plays a primary role in modulating the synthesis of polyphenols and antioxidant compounds in bean seeds. For example, the study conducted by Nadezkin et al. [46] showed that variations in the ratios of nitrogen, phosphorus, and potassium in chemical fertilizers led to corresponding changes in the protein content of Lika and Cinderella green bean seeds. Karavidas et al. [23] found that common bean pods grown under organic farming practices had higher antioxidant compound contents than those from conventional farming. In terms of water management, Saleh et al. [27] showed that both water deficit and excess reduced the accumulation of macro- and microelements and protein in Paulista and Bronco green bean seeds, with irrigation at 80% of evapotranspiration being the most effective.

Despite the challenges posed by environmental stresses and resource limitations, *Phaseolus coccineus* L. exhibits significant genetic variability, offering valuable opportunities for breeding programs aimed at improving tolerance to biotic and abiotic stress [47]. Therefore, exploiting local genetic resources, such as traditional cultivars and indigenous populations, becomes essential for diversifying the genetic base of crop species. These have valuable adaptive traits acquired through natural and agricultural selection, including abiotic stress tolerance, disease and pest resistance [48]. Studying and integrating these genetic resources into breeding programs can support the development of modern, resilient, and sustainable crop varieties adapted to climate change and the degradation of natural resources [48]. Furthermore, to optimize yields, it is essential to combine balanced fertilization with the

use of high-performing cultivars, appropriate plant spacing, and efficient irrigation management [32,33,49]. Implementing integrated water and nutrient management strategies alongside drought-tolerant *P. coccineus* genotypes is particularly important in the face of climate change and increasing water scarcity, ensuring the sustainability and productivity of cultivation systems.

In this context, the present study aimed to investigate the individual and combined effects of three runner bean cultivars (Cozia1, Cozia2, and Cozia3), two irrigation regimes ($2000 \text{ m}^3 \cdot \text{ha}^{-1}$ and $2500 \text{ m}^3 \cdot \text{ha}^{-1}$), and three fertilization treatments (chemical, organic, and unfertilized) on a wide range of physiological, morphological, and biochemical parameters. These include photosynthetic assimilation rate, chlorophyll content, pod and bean yield traits, and bean quality indicators such as antioxidant activity and total phenolic content. Therefore, this integrative approach focuses on identifying the optimal management practices that enhance yield and quality, thereby supporting the sustainable and efficient cultivation of runner beans in temperate regions such as Romania.

2. Materials and Methods

2.1. The Design and the Experimental Protocol

The experiment was conducted in 2022 and 2023 at the vegetable cultivation experimental open field of V. Adamachi farm, part of the Iasi University of Life Sciences, located in the northeastern part of Romania. The experimental plot was situated at a latitude of $47^\circ 11' 33.50'' \text{ N}$ and a longitude of $27^\circ 33' 2.58'' \text{ E}$, at an altitude of 100 m. The soil in this area is classified as loam-clay chernozem, with a pH of approximately 7.2 [50]. The experiment was set up on 20 May of each year and finished on 31 October.

Three key aspects of the technology for growing runner beans were studied: genotype, irrigation norms, and fertilization regimes. The experiment was structured using a randomized split-split plot design with three replications, as illustrated in Figure S1. Each replication consisted of a regular square pyramid arrangement of eight nests. Three seeds were sown per nest at a depth of 4 cm. After emergence, thinning was performed to retain two plants per nest, resulting in an average planting density of approximately 12,500 nests per hectare. To support plant growth, a bamboo staking system with a height of 2.7 m was installed (Figure 1).



(a)



(b)

Figure 1. Crop aspects at (a) the beginning of the growing season and (b) in the middle of the growing season.

Three local populations of runner beans represented the genotype factor: Cozia1, Cozia2, and Cozia3, which originated from Cozia in Iasi County. These populations share several common characteristics, including a climbing growth habit, white flowers, green pods, completely white beans, and a thousand-grain weight (TGW) exceeding 1300 g.

Irrigation was applied at two levels: $2000 \text{ m}^3 \cdot \text{ha}^{-1}$ (IR1) and $2500 \text{ m}^3 \cdot \text{ha}^{-1}$ (IR2) through a drip irrigation system, without taking precipitation into account. A total of 20 irrigation events were performed at weekly intervals, each providing $100 \text{ m}^3 \cdot \text{ha}^{-1}$ in IR1 and $125 \text{ m}^3 \cdot \text{ha}^{-1}$ in IR2. The two irrigation regimes were established considering the climatic conditions of the area, evidence from the literature [27–29], and previous research conducted in the same experimental field by Teliban et al. [31]. During the growing season, an additional 241 mm of precipitation fell in 2022 and 246 mm in 2023, based on data from Meteostat.net [51] (Figure 2).

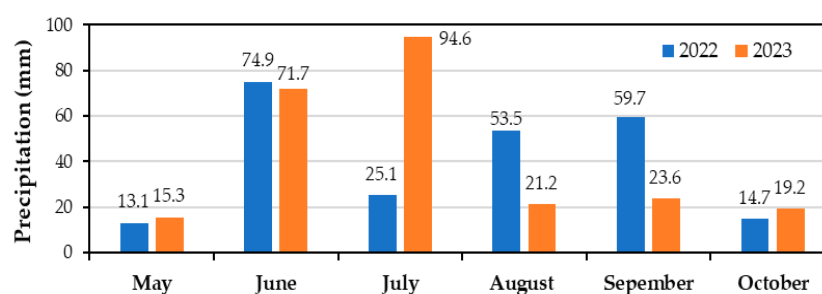


Figure 2. Precipitations registered (mm) during the growing season (20.05–31.10) in 2022 and 2023.

In terms of fertilization, three different regimes were applied: organic fertilization (OR), chemical fertilization (CH), and an unfertilized control (UF). In the organic fertilization variant, poultry manure was applied at a rate of $1875 \text{ kg} \cdot \text{ha}^{-1}$ (50% of the total amount at sowing, 25% after the appearance of the first flowers, and 25% after the formation of the first pods). The manure contained 4% total nitrogen, 4% phosphorus pentoxide, 4% potassium oxide, 0.5% water-soluble magnesium oxide, and 41% organic biochar. The chemical fertilization (CH) involved two types of NPK fertilizers. The first, NPK–14:40:5, was applied at a total dose of $320 \text{ kg} \cdot \text{ha}^{-1}$, with two-thirds applied as basal fertilization and one-third after the appearance of the first flowers. Its chemical composition was 14% total nitrogen (all ammonium nitrogen), 40% phosphorus anhydride, 5% potassium oxide, and 13% sulfuric anhydride, along with trace elements including 0.10% boron, iron, and zinc, and 0.05% copper, and 0.01% molybdenum. The second fertilizer, NPK–23:5:5, contained 23% total nitrogen (17% ammonium nitrogen and 6% nitrate nitrogen), 10% phosphorus pentoxide, 5% potassium oxide, and 29% sulfuric anhydride, along with 0.10% iron and zinc, and 0.05% manganese as trace elements. A total of $65 \text{ kg} \cdot \text{ha}^{-1}$ of NPK–23:5:5 was applied after the formation of the first pods. Given that organic fertilizers release nutrients more slowly than the immediate availability of chemical fertilizers, 25% more macronutrients were applied through organic fertilisation to meet the nutrient requirements of runner beans [52].

Throughout the growing season, crop maintenance activities were carried out following established guidelines from the literature [53,54]. The activities included training the plants onto the support system, manual pruning, and inter-row weeding, taking care to avoid damage to the irrigation system. Insecticide treatments (mix of Mavrik, Mospilan, Karatezeon) were applied prior to flowering and again after flowering, while fungicide treatments (mix of Alliete, Score, Champ, Captan) were carried out when weather conditions favored pathogen development. Pinching (removal of the shoot apex to promote branching) was carried out in two stages when plants reached 60–80 cm in length and then 100–130 cm. Additionally, variations in temperature, humidity, and dew point were

systematically monitored using Data Logger® DT-171T digital device (CEM Instruments, Shenzhen, China), which continuously recorded data from the planting phase to the harvest (Figure 3).

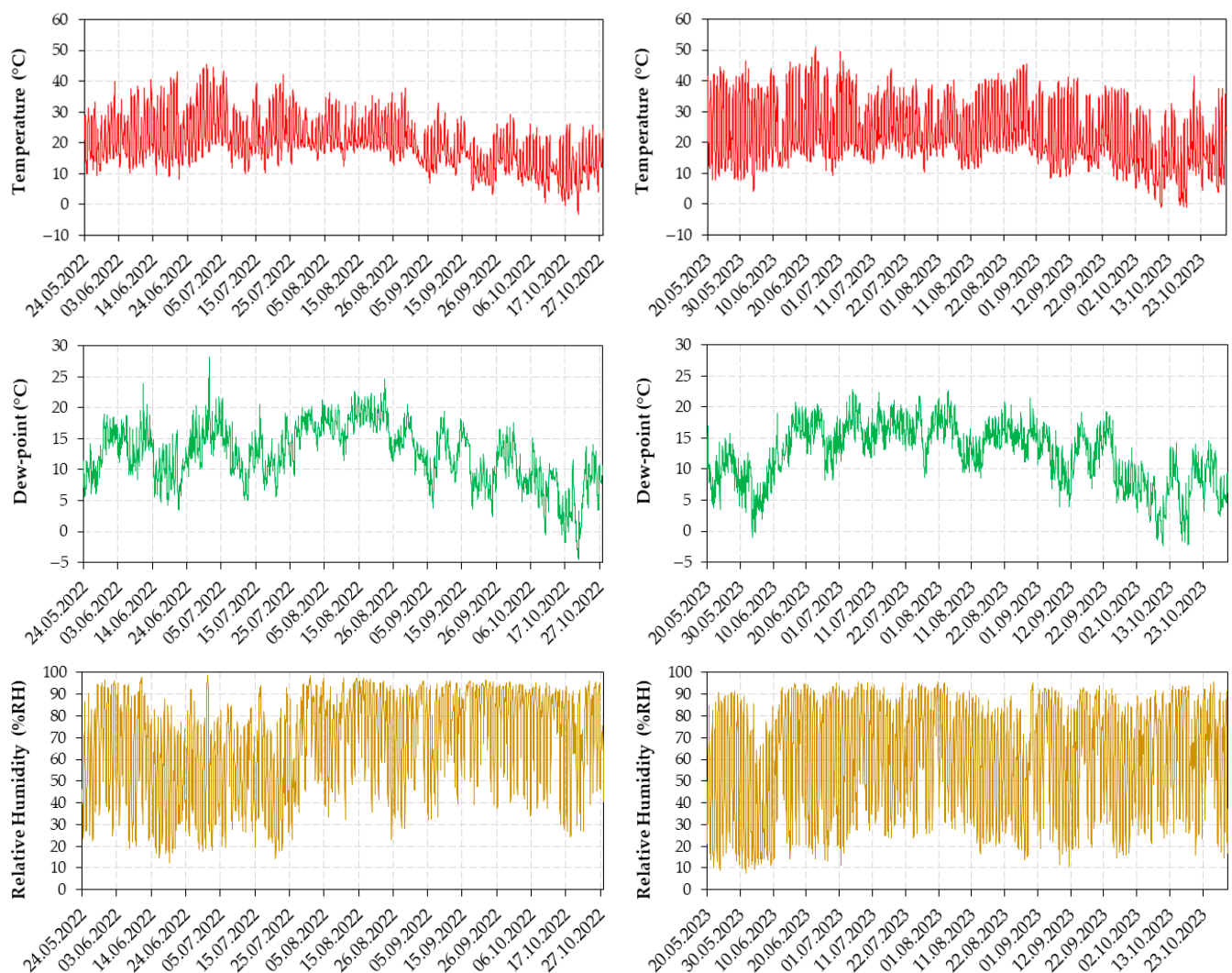


Figure 3. Variations in temperature, dew point and relative humidity at plant level during the growing season in 2022 and 2023.

2.2. Methods of Analysis of the Analyzed Parameters

The individual and combined effects of the studied factors on physiological parameters were evaluated through measurements taken midway through the growing season, specifically during growth stage BBCH 71. Leaf gas exchange, expressed as assimilation rate (A) in $\mu\text{mol m}^{-2}\cdot\text{s}^{-1}$, was measured using the portable LCpro T[®] system (ADC BioScientific Ltd., Hoddesdon, Hertfordshire, UK). The chlorophyll content index (CCI) was determined using the portable CCM 200plus device (Opti-Sciences, ADC BioScientific Ltd., Birmingham, UK).

After harvesting, the quantitative characteristics of the pods—such as the number of pods per plant, beans per pod, as well as the percentage weights of beans and pericarp—were recorded. Additionally, measurements included pod length (cm) and width (mm). Following the pod analysis, a quantitative assessment of the beans was conducted, measuring bean length, width, and thickness (all in millimetres), as well as the thousand-grain weight (TGW in grams), and yield per hectare (kilograms). The quality

assessments of the beans, including total polyphenol content (TPC) and antioxidant activity, as determined by both DPPH and ABTS methods, completed the analysis cycle.

Total polyphenol content (TPC) was measured using the Folin–Ciocalteu reagent (Sigma-Aldrich, Steinheim am Albuch, Germany) following the Slinkard and Singleton method [55]. The experimental protocol involved mixing 10 µL of hydrophilic extract with 175 µL of distilled water and 12 µL of Folin–Ciocalteu reagent. After a 3 min reaction time, 30 µL of a 20% aqueous sodium carbonate solution was added, and the mixture was incubated in the dark for 60 min. After the incubation, absorbance was measured at 765 nm using a microplate spectrophotometer (Thermo Scientific Multiskan GO, Vantaa, Finland). The polyphenol content was quantified by comparing the readings to a standard curve created using gallic acid solutions of known concentrations, prepared in a similar manner. The results are expressed in milligrams of gallic acid equivalents per 100 g of dry weight (mg GAE·100 g^{−1} d.w.) [56].

The antioxidant activity, assessed using the DPPH method, involved preparing a reagent by dissolving 3.5 mg of DPPH in 10 mL of methanol. The absorbance was adjusted to 0.98 ± 0.02 at 515 nm at a microplate spectrophotometer (Thermo Scientific Multiskan GO, Vantaa, Finland). Then, 100 µL of the DPPH solution and 10 µL of the sample extract (supernatant) or Trolox standard solutions were added to the microplate wells, and absorbance was measured at 515 nm. After the initial reading, DPPH reagent was added, and the mixture was left for 60 min before taking a second measurement at 515 nm. A calibration curve was established using Trolox solutions ranging from 50 to 3000 µM in methanol. The antioxidant capacity was determined by comparing the sample readings to the standards. Results are expressed as micromoles of Trolox equivalents per gram of dry matter (mmol TE·100 g^{−1} d.w.).

To assess antioxidant capacity using the ABTS assay, a reaction mixture was prepared by combining 175 µL of distilled water, 190 µL of ABTS solution, and 10 µL of plant extract (supernatant). The mixture was then incubated in the dark for 15 min prior to absorbance measurement. The ABTS solution was prepared by dissolving 38.6 mg of ABTS in 10 mL of 2.45 mM potassium persulfate, which was obtained by dissolving 334.4 mg of potassium persulfate in 500 mL of distilled water. This solution was left to incubate for 16 h in the dark to allow full generation of the ABTS radical required for the assay. Absorbance was measured at 730 nm using a Thermo Scientific Multiskan GO microplate spectrophotometer (Vantaa, Finland). A calibration curve was prepared using Trolox standards dissolved in 0.1 mM methanol and subjected to the same analytical procedure as the samples. Antioxidant activity was expressed as micromoles of Trolox equivalents per gram of dry weight (mmol TE·100 g^{−1} d.w.) [56,57].

All analyses were performed in triplicate and the mean values and standard deviation were calculated for each sample.

2.3. Statistical Analysis of Results

To analyze the relationships between variables and identify significant differences in the dataset, several statistical techniques were applied. In the first stage, analysis of variance (ANOVA) was employed to assess statistically significant differences between groups. Subsequently, the Duncan post hoc test at a significance level of $p \leq 0.05$ was applied to compare means. These analyses were performed using SPSS software, version 26 (IBM Corp., Armonk, NY, USA), and results were presented as mean ± standard error (SE). To gain a deeper understanding of the structure and interrelations among traits across the different combinations between Cozia bean cultivars, irrigation regimes, and fertilisation treatments, multivariate analysis was performed using Principal Component Analysis (PCA) alongside Pearson correlation. The analyses were carried out using the OriginLab

Pro 2025b free trial (OriginLab Corporation, Northampton, MA, USA). Furthermore, a three-way ANOVA was performed to assess the influence and interactions among genotype, irrigation regime, and fertilization practices on the physiological, morphological, and biochemical parameters analysed. The analysis was performed using SPSS software, version 26 (IBM Corp., Armonk, NY, USA)

3. Results

3.1. Influence of Experimental Factors on Physiological Indicators

The rate of photosynthetic assimilation in the leaves of runner beans varied significantly with cultivar and fertilization regime, while no significant differences were found with irrigation norm (Figure 4a). Among the different genotypes, the cultivar Cozia1 exhibited the highest photosynthetic assimilation rate at $11.92 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$, while the cultivar Cozia3 had the lowest rate at $10.64 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$. In terms of fertilization, the organically fertilized variant achieved the highest assimilation rate of $11.53 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$. This rate is significantly higher compared to the non-fertilized variant ($10.92 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$), but not significantly different from the chemically fertilized variant ($11.21 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$).

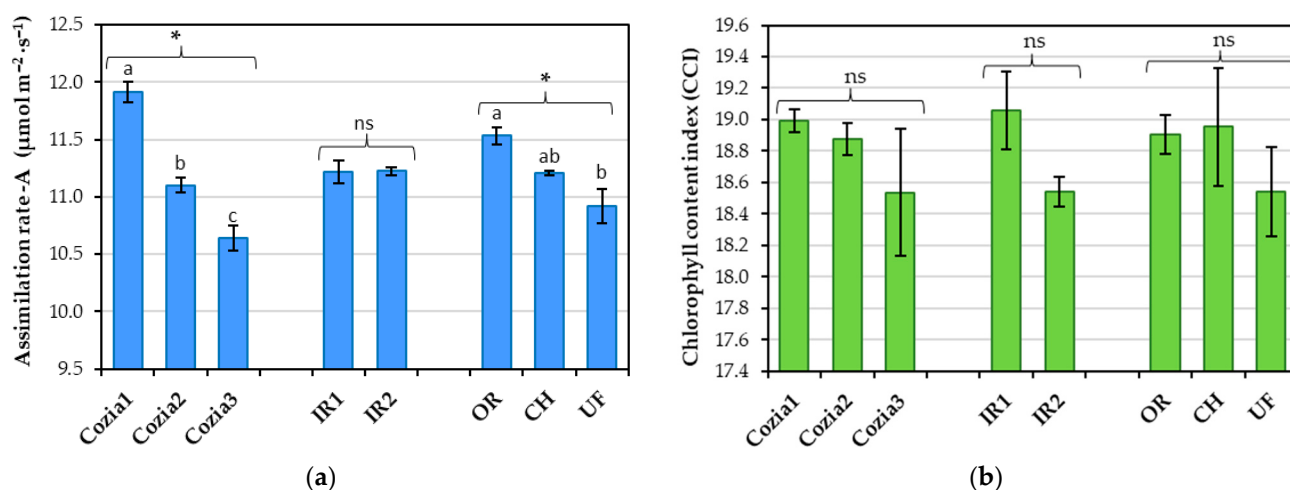


Figure 4. (a) Photosynthetic assimilation rate—A and (b) chlorophyll content index—CCI in runner bean leaves under individual influence of cultivar, irrigation, and fertilization regime. Values are presented as mean $\pm$ standard error of individual replicates. Within each factor: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1— $2000 \text{ m}^3\cdot\text{ha}^{-1}$ irrigation; IR2— $2500 \text{ m}^3\cdot\text{ha}^{-1}$ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

The analysis of the individual impact of the experimental factors on chlorophyll pigment content (CCI) showed no statistically significant effects (Figure 4b). Among the cultivars, Cozia1 recorded the highest CCI value (18.99), followed by Cozia2 (18.88), while Cozia3 had the lowest content (18.54). In terms of irrigation, the highest CCI values were observed under the IR1 norm. Regarding fertilization, the treatment with chemical fertilizers resulted in the highest CCI (18.95), closely followed by organic fertilization (18.90).

Photosynthetic assimilation and chlorophyll content index both exhibited statistically significant differences due to the interaction between genotype and irrigation (Figure 5). The Cozia1 $\times$ IR1 variant achieved the highest CO_2 assimilation rate of $12.38 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$, which is 14% higher than the Cozia3 $\times$ IR1 ($10.63 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$), Cozia2 $\times$ IR1 ($10.64 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$), and Cozia3 $\times$ IR2 ($10.65 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$) variants, which recorded the lowest rates. The Cozia2 $\times$ IR2 and Cozia1 $\times$ IR2 variants produced intermediate results with rates of 11.57 and $11.45 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$, respectively. Regarding

the CCI analysis, the Cozia1 $\times$ IR1 variant exhibited a chlorophyll content (19.54) approximately 6% higher compared to the Cozia3 $\times$ IR2 and Cozia1 $\times$ IR2 variants. In contrast, no significant differences were observed compared to the other experimental variants.

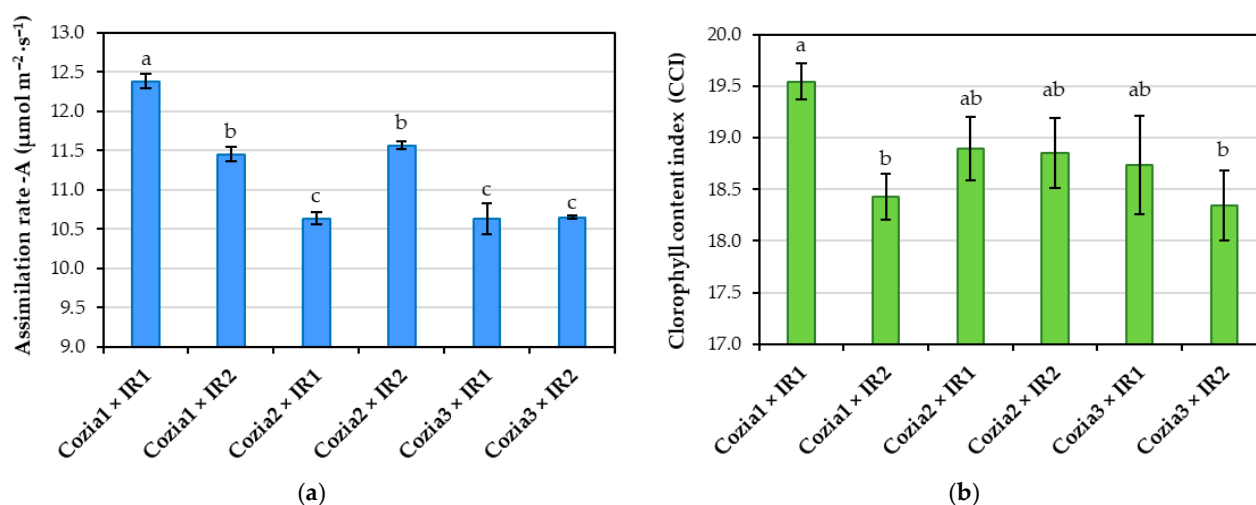


Figure 5. (a) Photosynthetic assimilation rate—A and (b) chlorophyll content index—CCI in runner bean leaves under the combined influence of cultivar and irrigation. Values are presented as mean $\pm$ standard error of individual replicates. Different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1—2000 $\text{m}^3\cdot\text{ha}^{-1}$ irrigation; IR2—2500 $\text{m}^3\cdot\text{ha}^{-1}$ irrigation.

Analysis of the data on the interaction between cultivar and fertilization also revealed significant differences in both the photosynthetic assimilation rate and the chlorophyll content index (CCI). For example, the combinations Cozia1 $\times$ OR, Cozia1 $\times$ CH, Cozia2 $\times$ UF, and Cozia3 $\times$ OR exhibited the highest values, which were significantly greater than those of the other variants. Furthermore, as shown in Figure 6a, the unfertilized Cozia3 variant recorded the lowest photosynthetic assimilation rate ($10.34 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$), a value significantly lower than those observed in all other experimental combinations. Regarding CCI (Figure 6b), the highest value was observed in the Cozia1 $\times$ CH variant at 19.73 CCI, which is 8% higher than the Cozia3 $\times$ CH and Cozia1 $\times$ OR variants, with values of 18.21 and 18.35 CCI, respectively. The other experimental variants showed intermediate values, ranging from 18.52 to 19.18 CCI, with no statistically significant differences compared to either the highest or lowest values.

Considering the interaction between irrigation and fertilisation, it was found that their combination caused significant differences among the experimental variants in both analysed physiological indicators (Figure 7). The highest photosynthetic assimilation rate was recorded in the IR1 $\times$ OR variant ($11.92 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$), showing no significant difference only in comparison with the IR2 $\times$ CH variant. The lowest value was observed in the IR1 $\times$ CH variant ($10.82 \mu\text{mol m}^{-2}\cdot\text{s}^{-1}$). For the CCI indicator, the highest value was observed in the IR1 $\times$ CH variant (19.61 CCI). This was significantly higher only compared to the IR2 $\times$ CH and IR2 $\times$ UF variants, while the differences with the other variants were not statistically significant.

The data on the interaction among the three considered factors revealed that the Cozia1 cultivar, under the influence of IR2 $\times$ UF, recorded the lowest values for both the photosynthetic assimilation rate and CCI. In contrast, the Cozia2 cultivar, under the same conditions, exhibited the highest values for these indicators. For Cozia3, the IR1 $\times$ UF combination proved to be the most unfavourable in terms of both physiological parameters (Figure 8). Nevertheless, statistical analysis showed that the combination of factors caused the greatest

variation in the photosynthetic assimilation rate, while its impact on CCI was comparatively less significant (Figure 8). Significant differences in the photosynthetic assimilation rate values for the Cozia1 cultivar were observed between the Cozia1 $\times$ IR1 $\times$ OR combination and the other experimental variants, as well as between the Cozia1 $\times$ IR1 $\times$ UF combination and the rest of the treatments. For the Cozia2 cultivar, the IR2 $\times$ UF combination resulted in a photosynthetic assimilation rate that was statistically significantly higher than those recorded under the other treatment combinations. Similarly, in the case of Cozia3, the IR1 $\times$ OR treatment led to a statistically significant increase in photosynthetic assimilation rate compared to the remaining interactions between factors.

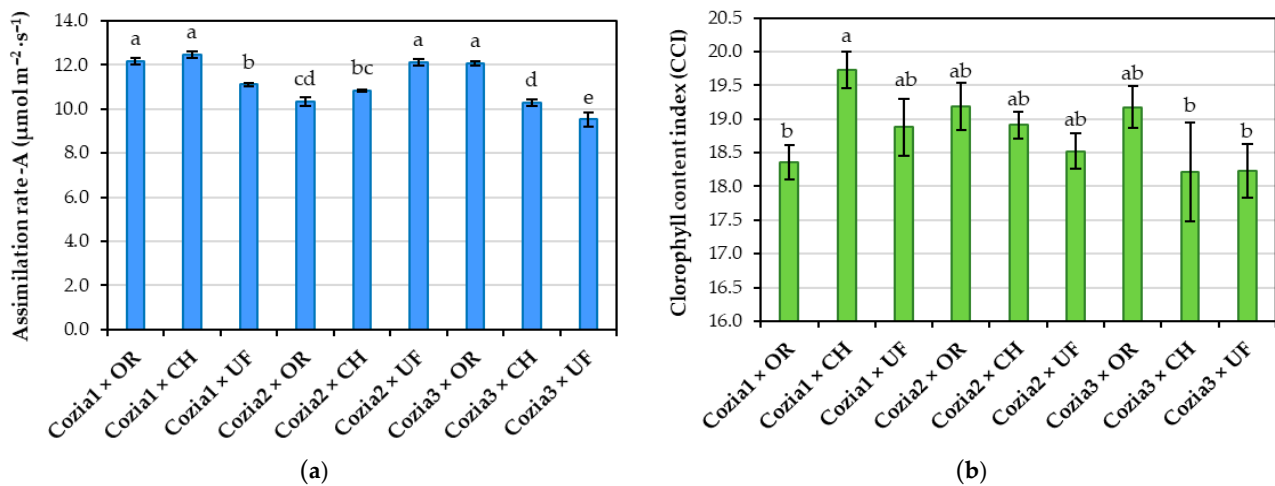


Figure 6. (a) Photosynthetic assimilation rate—A and (b) chlorophyll content index—CCI in runner bean leaves under the combined influence of cultivar and fertilization regime. Values are presented as mean $\pm$ standard error of individual replicates. Different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

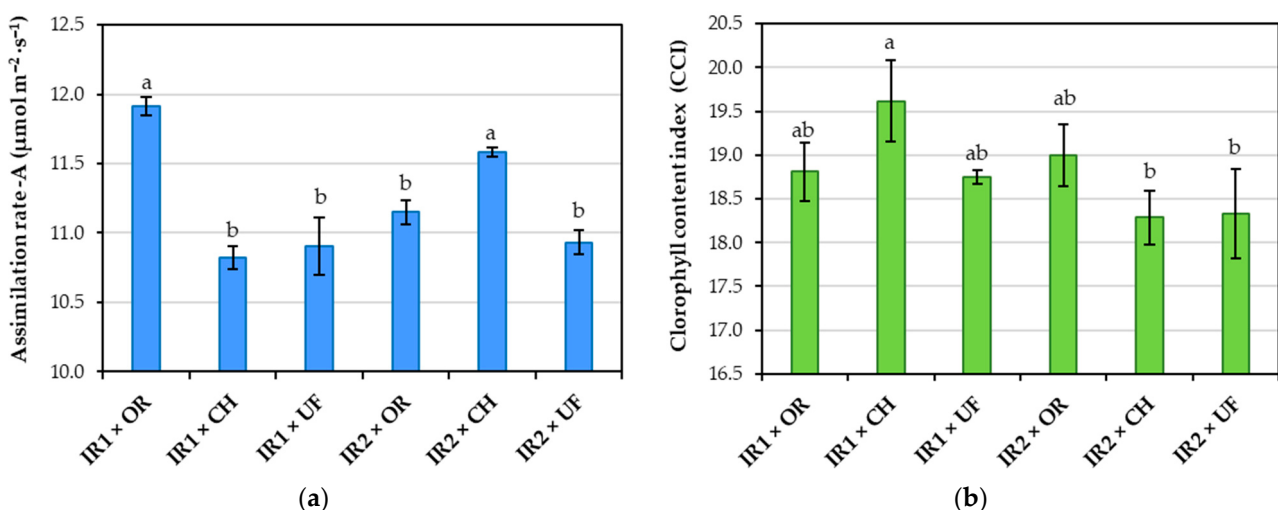


Figure 7. (a) Photosynthetic assimilation rate—A and (b) chlorophyll content index—CCI in runner bean leaves under the combined influence of irrigation and fertilization regime. Values are presented as mean $\pm$ standard error of individual replicates. Different letters represent statistical differences between variants at $p \leq 0.05$ according to the Duncan test, with 'a' representing the highest values. IR1—2000 $\text{m}^3 \cdot \text{ha}^{-1}$ irrigation; IR2—2500 $\text{m}^3 \cdot \text{ha}^{-1}$ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

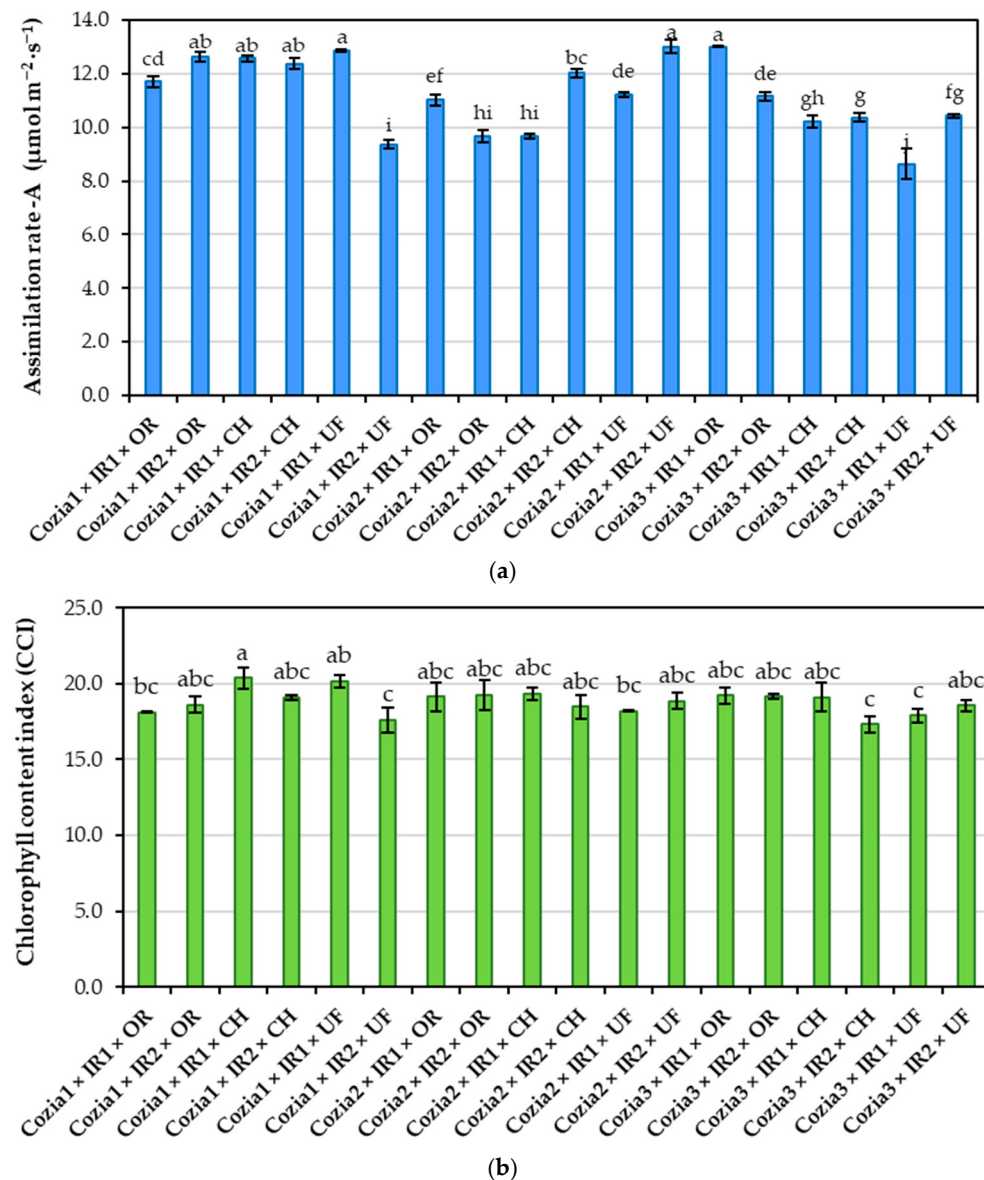


Figure 8. (a) Photosynthetic assimilation rate—A and (b) chlorophyll content index—CCI in runner bean leaves under the combined influence of cultivar, irrigation, and fertilization regime. Values are presented as mean $\pm$ standard error of individual replicates. The different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1—2000 $\text{m}^3 \cdot \text{ha}^{-1}$ irrigation; IR2—2500 $\text{m}^3 \cdot \text{ha}^{-1}$ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

Regarding the CCI, the highest value was recorded in the Cozia1 $\times$ IR1 $\times$ CH variant, with a mean CCI of 20.38. This value was statistically significantly higher (at $p < 0.05$) only when compared with the levels determined in the treatment combinations: Cozia1 $\times$ IR1 $\times$ OR, Cozia1 $\times$ IR2 $\times$ UF, Cozia2 $\times$ IR1 $\times$ UF, Cozia3 $\times$ IR2 $\times$ CH, and Cozia3 $\times$ IR1 $\times$ UF. No statistically significant differences were observed either between Cozia1 $\times$ IR1 $\times$ CH and the remaining treatments, or among the remaining treatments themselves.

3.2. Influence of Experimental Factors on Biometric Indicators

The analysis of biometric indicators revealed that their variation was significantly more influenced by genotype and irrigation regime than by the type of fertilizer applied, as shown in Tables 1 and 2. The effects of genotype and irrigation were consistently

observed across multiple traits, indicating a more substantial impact of these factors on plant morphology. Genotypic variation induced statistically significant differences in all indicators except for the number of seeds per pod. The Cozia1 cultivar is distinguished by higher pericarp weight percentage, pod length, bean length, bean thickness, and thousand grain weight (TGW). Conversely, Cozia2 has higher values for the number of pods per plant, seed weight percentage, and bean width. Cozia3 demonstrates significantly larger pod width and grain yield compared to the other cultivars.

Table 1. Individual influences of genotype, irrigation and fertilization on the characteristics of runner bean pods.

Treatment	Pods per Plant	Seeds per Pod	Seed Weight Percentage (%)	Pericarp Weight Percentage (%)	Pods Length (cm)	Pods Width (mm)
Cozia1	29.72 ± 0.22 b	2.30 ± 0.02	74.04 ± 0.16 b	25.96 ± 0.16 a	10.16 ± 0.03 a	18.19 ± 0.09 b
Cozia2	33.30 ± 0.07 a	2.30 ± 0.02	75.94 ± 0.20 a	24.06 ± 0.20 b	9.70 ± 0.02 b	18.50 ± 0.03 b
Cozia3	32.84 ± 0.19 a	2.30 ± 0.01	74.32 ± 0.34 b	25.68 ± 0.34 a	9.75 ± 0.09 b	19.06 ± 0.14 a
Signification	*	ns	*	*	*	*
IR1	30.46 ± 0.47	2.28 ± 0.01	75.05 ± 0.06	24.95 ± 0.06	9.80 ± 0.07	18.40 ± 0.22
IR2	33.45 ± 0.29	2.31 ± 0.02	74.48 ± 0.08	25.52 ± 0.08	9.94 ± 0.03	18.77 ± 0.09
Signification	*	ns	*	*	ns	ns
OR	32.23 ± 0.22 b	2.31 ± 0.02	75.06 ± 0.27	24.94 ± 0.27	9.95 ± 0.03	18.28 ± 0.10 b
CH	33.85 ± 0.31 a	2.32 ± 0.01	74.70 ± 0.16	25.30 ± 0.16	9.93 ± 0.06	18.88 ± 0.03 a
UF	29.78 ± 0.52 c	2.26 ± 0.02	74.54 ± 0.27	25.46 ± 0.27	9.72 ± 0.12	18.60 ± 0.15 ab
Signification	*	ns	ns	ns	ns	*

The values are presented as mean ± standard error of individual replicates. Within each column, and factor group: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m³·ha^{−1} irrigation; IR2—2500 m³·ha^{−1} irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

Table 2. Individual influences of the genotype, irrigation and fertilization on the seed morphological and yield traits of runner bean.

Treatment	Beans Length (mm)	Beans Width (mm)	Beans Thickness (mm)	TGW (g)	Grain Yield (kg·ha ^{−1})
Cozia1	21.01 ± 0.16 a	13.03 ± 0.02 b	8.69 ± 0.10 a	1444.40 ± 10.00 a	2505.60 ± 39.54 c
Cozia2	20.05 ± 0.02 b	13.64 ± 0.02 a	8.61 ± 0.06 a	1412.84 ± 14.62 ab	2674.23 ± 17.26 b
Cozia3	20.00 ± 0.17 b	13.45 ± 0.11 a	7.98 ± 0.02 b	1388.69 ± 8.01 b	2951.81 ± 19.94 a
Signification	*	*	*	*	*
IR1	20.34 ± 0.03	13.25 ± 0.10	8.33 ± 0.04	1407.88 ± 3.38	2648.38 ± 40.19
IR2	20.37 ± 0.02	13.49 ± 0.02	8.52 ± 0.06	1422.74 ± 10.68	2772.70 ± 27.52
Signification	ns	ns	ns	ns	ns
OR	20.40 ± 0.05	13.29 ± 0.03	8.49 ± 0.06	1405.71 ± 12.49	2807.84 ± 32.11 a
CH	20.28 ± 0.01	13.54 ± 0.03	8.47 ± 0.06	1409.35 ± 20.03	2836.43 ± 68.70 a
UF	20.37 ± 0.06	13.28 ± 0.12	8.32 ± 0.10	1430.88 ± 4.96	2487.37 ± 57.67 b
Signification	ns	ns	ns	ns	*

The values are presented as mean ± standard error of individual replicates. Within each column, and factor group: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters represent statistical differences between variants, where 'a' represents the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m³·ha^{−1} irrigation; IR2—2500 m³·ha^{−1} irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TGW—thousand-grain weight.

The irrigation regime mainly affected a few biometric indicators: the number of pods per plant, seed weight percentage, and pericarp weight percentage. While most traits did not differ significantly, the IR2 treatment generally exhibited the highest values for most parameters analysed, except for seed weight percentage.

The overall impact of fertilizer type was relatively minor, and most measured parameters did not show statistically significant differences. Nevertheless, notable differences were found in the number of pods per plant, pod width, and grain yield, with chemical fertilization yielding the highest values for these traits (33.85 pods per plant, a pod width of 18.88 mm, and a grain yield of 2836.43 kg·ha^{−1}). Conversely, the organically fertilized variant exhibited the highest values for seed weight percentage (75.06%), pod length (9.95 cm), bean length (20.40 mm), and bean thickness (8.49 mm), though these were not statistically significant. The control (unfertilized) treatment resulted in the highest pericarp weight percentage (25.46%) and TGW of 1430.88 g.

As shown in Tables 3 and 4, the genotype × irrigation, genotype × fertilization, and irrigation × fertilization interactions significantly influenced both the quantitative traits of runner bean pods and beans.

Table 3. Influence of genotype × irrigation, genotype × fertilisation, and irrigation × fertilisation interactions on the characteristics of runner bean pods.

Treatment	Pods per Plant	Seeds per Pod	Seed Weight Percentage (%)	Pericarp Weight Percentage (%)	Pods Length (cm)	Pods Width (mm)
Cozia1 × IR1	30.78 ± 1.92 b	2.29 ± 0.02	74.39 ± 0.20 b	25.61 ± 0.20 a	10.20 ± 0.05 a	18.17 ± 0.21 b
Cozia1 × IR2	28.67 ± 1.50 b	2.31 ± 0.02	73.69 ± 0.23 b	26.31 ± 0.23 a	10.12 ± 0.01 ab	18.21 ± 0.09 b
Cozia2 × IR1	29.54 ± 0.61 b	2.29 ± 0.01	75.97 ± 0.46 a	24.03 ± 0.46 b	9.60 ± 0.03 d	18.29 ± 0.11 b
Cozia2 × IR2	37.05 ± 0.58 a	2.31 ± 0.02	75.90 ± 0.23 a	24.10 ± 0.23 b	9.80 ± 0.02 cd	18.70 ± 0.09 b
Cozia3 × IR1	31.06 ± 0.53 b	2.26 ± 0.04	74.80 ± 0.12 ab	25.20 ± 0.12 ab	9.62 ± 0.18 cd	18.75 ± 0.34 b
Cozia3 × IR2	34.63 ± 0.17 a	2.33 ± 0.01	73.84 ± 0.70 b	26.16 ± 0.70 a	9.88 ± 0.05 bc	19.38 ± 0.17 a
Signification	*	ns	*	*	*	*
Cozia1 × OR	28.93 ± 0.32 c	2.29 ± 0.02	74.00 ± 0.41 cd	26.00 ± 0.41 ab	10.22 ± 0.03 ab	17.91 ± 0.09 d
Cozia1 × CH	29.89 ± 0.38 c	2.34 ± 0.03	73.92 ± 0.34 cd	26.08 ± 0.34 ab	10.36 ± 0.05 a	18.50 ± 0.17 bcd
Cozia1 × UF	30.34 ± 0.38 c	2.27 ± 0.01	74.21 ± 0.39 cd	25.79 ± 0.39 ab	9.91 ± 0.10 bc	18.16 ± 0.11 cd
Cozia2 × OR	34.44 ± 0.26 b	2.35 ± 0.05	76.20 ± 0.55 a	23.80 ± 0.55 d	9.81 ± 0.08 c	18.01 ± 0.27 cd
Cozia2 × CH	36.98 ± 0.59 a	2.31 ± 0.01	75.73 ± 0.02 ab	24.27 ± 0.02 cd	9.62 ± 0.09 c	18.49 ± 0.10 bcd
Cozia2 × UF	28.47 ± 0.39 c	2.24 ± 0.01	75.88 ± 0.32 a	24.12 ± 0.32 d	9.67 ± 0.06 c	19.01 ± 0.13 b
Cozia3 × OR	33.33 ± 0.67 b	2.31 ± 0.01	74.99 ± 0.09 abc	25.01 ± 0.09 bcd	9.84 ± 0.01 c	18.92 ± 0.07 b
Cozia3 × CH	34.67 ± 1.19 b	2.30 ± 0.02	74.44 ± 0.83 bcd	25.56 ± 0.83 abc	9.82 ± 0.08 c	19.66 ± 0.17 a
Cozia3 × UF	30.52 ± 1.20 c	2.28 ± 0.08	73.53 ± 0.20 d	26.47 ± 0.20 a	9.58 ± 0.30 c	18.61 ± 0.47 bc
Signification	*	ns	*	*	*	*
IR1 × OR	31.18 ± 0.61 c	2.28 ± 0.03 bc	74.27 ± 0.24 bc	25.73 ± 0.24 ab	9.83 ± 0.04 a	18.21 ± 0.30 c
IR1 × CH	31.01 ± 0.11 cd	2.39 ± 0.01 a	75.98 ± 0.15 a	24.02 ± 0.15 c	10.09 ± 0.05 a	18.73 ± 0.07 abc
IR1 × UF	29.18 ± 1.14 d	2.17 ± 0.05 d	74.89 ± 0.11 ab	25.11 ± 0.11 bc	9.49 ± 0.23 b	18.27 ± 0.32 c
IR2 × OR	33.28 ± 0.20 b	2.35 ± 0.02 ab	75.85 ± 0.52 a	24.15 ± 0.52 c	10.08 ± 0.04 a	18.34 ± 0.11 bc
IR2 × CH	36.69 ± 0.63 a	2.24 ± 0.03 cd	73.41 ± 0.17 c	26.59 ± 0.17 a	9.78 ± 0.08 ab	19.03 ± 0.12 a
IR2 × UF	30.38 ± 0.10 cd	2.36 ± 0.01 ab	74.18 ± 0.59 bc	25.82 ± 0.59 ab	9.95 ± 0.05 a	18.92 ± 0.07 ab
Signification	*	*	*	*	*	*

The values are presented as mean ± standard error of individual replicates. Within each column, and for each combination of two factors: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m³·ha^{−1} irrigation; IR2—2500 m³·ha^{−1} irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

The genotype × irrigation interaction significantly influenced all pod and seed traits, except the number of seeds per pod, which showed only minor variation (2.26–2.33). The highest number of pods per plant (37.05) was recorded in Cozia2 × IR2, exceeding Cozia1 × IR2 by over 23%. Seed weight percentage ranged from 73.69% (Cozia1 × IR2) to 75.97% (Cozia2 × IR1), with an inversely proportional relationship to pericarp weight percentage. Cozia1 × IR1 produced the longest pods (10.20 cm), while Cozia3 × IR2 showed the greatest pod width (19.38 mm). Bean biometric traits were also strongly affected by this interaction. Cozia1 × IR1 achieved the highest seed length (21.22 mm) and TGW (1449.82 g), while Cozia3 × IR1 had the lowest values across most seed traits, including yield (2483.07 kg·ha^{−1}). In contrast, the highest yield (2995.21 kg·ha^{−1}) was recorded for Cozia3 × IR2, indicating a 17% increase due to the interaction.

Table 4. Influence of genotype $\times$ irrigation, genotype $\times$ fertilisation, and irrigation $\times$ fertilisation interactions on the seed morphological and yield traits of runner bean.

Treatment	Beans Length (mm)	Beans Width (mm)	Beans Thickness (mm)	TGW (g)	Grain Yield (kg·ha ⁻¹)
Cozia1 $\times$ IR1	21.22 $\pm$ 0.36 a	13.05 $\pm$ 0.09 b	8.62 $\pm$ 0.10 a	1449.82 $\pm$ 29.03 a	2528.13 $\pm$ 108.51 b
Cozia1 $\times$ IR2	20.80 $\pm$ 0.06 a	13.00 $\pm$ 0.04 b	8.77 $\pm$ 0.12 a	1438.99 $\pm$ 9.82 ab	2483.07 $\pm$ 29.48 b
Cozia2 $\times$ IR1	19.96 $\pm$ 0.10 b	13.55 $\pm$ 0.01 a	8.49 $\pm$ 0.09 a	1388.15 $\pm$ 19.39 b	2508.62 $\pm$ 19.20 b
Cozia2 $\times$ IR2	20.14 $\pm$ 0.07 b	13.73 $\pm$ 0.05 a	8.73 $\pm$ 0.07 a	1437.52 $\pm$ 10.89 ab	2839.83 $\pm$ 42.35 a
Cozia3 $\times$ IR1	19.83 $\pm$ 0.31 b	13.16 $\pm$ 0.23 b	7.89 $\pm$ 0.10 b	1385.69 $\pm$ 8.21 b	2908.40 $\pm$ 65.91 a
Cozia3 $\times$ IR2	20.16 $\pm$ 0.02 b	13.73 $\pm$ 0.03 a	8.08 $\pm$ 0.07 b	1391.70 $\pm$ 15.73 b	2995.21 $\pm$ 32.56 a
Signification	*	*	*	*	*
Cozia1 $\times$ OR	21.11 $\pm$ 0.03 ab	12.88 $\pm$ 0.02 c	8.69 $\pm$ 0.09 a	1455.05 $\pm$ 15.48 ab	2584.88 $\pm$ 1.39 bcd
Cozia1 $\times$ CH	20.69 $\pm$ 0.14 abc	13.25 $\pm$ 0.06 bc	8.69 $\pm$ 0.07 a	1453.49 $\pm$ 3.42 ab	2506.75 $\pm$ 55.26 cd
Cozia1 $\times$ UF	21.23 $\pm$ 0.58 a	12.94 $\pm$ 0.02 c	8.70 $\pm$ 0.22 a	1424.67 $\pm$ 11.69 abc	2425.17 $\pm$ 64.82 d
Cozia2 $\times$ OR	19.93 $\pm$ 0.12 cd	13.37 $\pm$ 0.04 b	8.71 $\pm$ 0.14 a	1352.81 $\pm$ 4.89 c	2745.76 $\pm$ 13.25 bc
Cozia2 $\times$ CH	19.92 $\pm$ 0.02 cd	13.59 $\pm$ 0.05 ab	8.78 $\pm$ 0.15 a	1382.65 $\pm$ 11.61 bc	2872.18 $\pm$ 65.49 ab
Cozia2 $\times$ UF	20.30 $\pm$ 0.17 bcd	13.97 $\pm$ 0.03 a	8.35 $\pm$ 0.03 ab	1503.05 $\pm$ 40.52 a	2404.74 $\pm$ 51.88 d
Cozia3 $\times$ OR	20.15 $\pm$ 0.08 cd	13.61 $\pm$ 0.07 ab	8.06 $\pm$ 0.04 bc	1409.25 $\pm$ 17.18 bc	3092.85 $\pm$ 85.37 a
Cozia3 $\times$ CH	20.25 $\pm$ 0.16 bcd	13.78 $\pm$ 0.09 a	7.96 $\pm$ 0.11 bc	1391.92 $\pm$ 52.65 bc	3130.37 $\pm$ 197.78 a
Cozia3 $\times$ UF	19.58 $\pm$ 0.56 d	12.95 $\pm$ 0.36 c	7.92 $\pm$ 0.18 c	1364.91 $\pm$ 19.04 c	2632.19 $\pm$ 153.27 bcd
Signification	*	*	*	*	*
IR1 $\times$ OR	20.33 $\pm$ 0.08	13.14 $\pm$ 0.07 bc	8.36 $\pm$ 0.05 ab	1374.10 $\pm$ 21.13 b	2621.90 $\pm$ 8.82 bc
IR1 $\times$ CH	20.34 $\pm$ 0.07	13.54 $\pm$ 0.02 a	8.47 $\pm$ 0.11 ab	1429.27 $\pm$ 19.03 ab	2800.98 $\pm$ 19.75 ab
IR1 $\times$ UF	20.35 $\pm$ 0.10	13.08 $\pm$ 0.25 c	8.17 $\pm$ 0.14 b	1420.29 $\pm$ 8.01 ab	2522.27 $\pm$ 125.06 c
IR2 $\times$ OR	20.46 $\pm$ 0.03	13.43 $\pm$ 0.02 ab	8.62 $\pm$ 0.14 a	1437.31 $\pm$ 7.82 a	2993.76 $\pm$ 55.51 a
IR2 $\times$ CH	20.24 $\pm$ 0.07	13.54 $\pm$ 0.04 a	8.48 $\pm$ 0.05 ab	1389.44 $\pm$ 22.45 ab	2871.88 $\pm$ 124.45 a
IR2 $\times$ UF	20.40 $\pm$ 0.02	13.49 $\pm$ 0.01 a	8.48 $\pm$ 0.08 ab	1441.47 $\pm$ 15.09 a	2452.47 $\pm$ 25.01 c
Signification	ns	*	*	*	*

The values are presented as mean $\pm$ standard error of individual replicates. Within each column, and for each combination of two factors: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m³·ha⁻¹ irrigation; IR2—2500 m³·ha⁻¹ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TGW—thousand-grain weight.

The genotype $\times$ fertilization interaction similarly affected all pod traits except seed number. The number of pods per plant ranged from 28.47 (Cozia2 $\times$ UF) to 36.98 (Cozia2 $\times$ CH), with a variation of up to 23%. The highest seed weight percentage (76.20%) was recorded in Cozia2 $\times$ OR, while the lowest (73.53%) was in Cozia3 $\times$ UF, showing an inverse relationship with pericarp content. Pod length varied from 9.58 cm (Cozia3 $\times$ UF) to 10.36 cm (Cozia1 $\times$ CH), and pod width had nearly a 9% difference, reaching 19.66 mm in Cozia3 $\times$ CH. The longest seed grains were observed in Cozia1 $\times$ UF at 21.23 mm, which is 7.77% taller than those in Cozia3 $\times$ UF (19.58 mm). The largest seed width and TGW were observed in Cozia2 $\times$ UF, with 13.97 mm and 1503.05 g, respectively. The smallest bean width was 12.88 mm for Cozia1 $\times$ OR, and the lightest TGW was 1352.81 g for Cozia2 $\times$ OR. Bean thickness varied approximately 10%, from 7.92 mm (Cozia3 $\times$ UF) to 8.78 mm (Cozia2 $\times$ CH). The highest yield was found in the Cozia3 $\times$ CH variant, at 3130.37 kg·ha⁻¹, while the lowest, 23% less, was in the Cozia2 $\times$ UF variant, with 2404.74 kg·ha⁻¹.

The irrigation $\times$ fertilization interaction significantly influenced all measured traits. IR2 $\times$ CH had the highest values for number of pods (36.69), pericarp percentage (26.59%) and pod width (19.03 mm), while IR1 $\times$ CH had the highest number of seeds per pod (2.39), seed weight percentage (75.98%) and pod length (10.09 cm). In contrast, IR1 $\times$ UF showed the lowest values for the number of pods (29.18), the number of seeds (2.17), and pod length (9.49 cm), illustrating the combined effect of limited water and nutrients. In terms of bean characteristics, the IR2 $\times$ OR variant had the highest values for bean length (20.46 mm),

bean thickness (8.62 mm) and yield (2993.76 kg·ha^{−1}). The widest beans (13.54 mm) were observed in IR1 × CH and IR2 × CH, while the narrowest (13.08 mm) occurred in IR1 × UF. The highest TGW was recorded in IR2 × UF (1441.47 g), while IR1 × OR had the lowest (1374.10 g). The shortest grains were found in IR2 × CH (20.24 mm), while IR1 × UF also recorded the smallest thickness (8.17 mm). Despite a high TGW, IR2 × UF had the lowest yield (2452.47 kg·ha^{−1}).

The three-way interaction among genotype, irrigation, and fertilization significantly influenced the traits studied. The evaluation revealed notable impacts on various characteristics, highlighting the complex interactions that affect pod and beans traits, as shown in Tables 5 and 6. The Cozia2 cultivar exhibited the highest number of pods per plant, with a total of 30 pods. In comparison, the Cozia2 × IR2 × CH variant produced an impressive 48.13 pods, while the Cozia2 × IR1 × CH variant had 25 pods. The number of seeds per pod varied, ranging from 2.10 in the Cozia2 × IR1 × UF variant to 2.43 in both the Cozia2 × IR1 × CH and Cozia3 × IR2 × UF variants. The highest seed weight percentage was found in the Cozia2 × IR1 × OR variant, at 76.77%, which was negatively correlated with pericarp weight percentage, recorded at 23.23%. Conversely, the Cozia1 × IR1 × OR variant had the highest pericarp weight percentage of 28.04%, which was negatively correlated with seed weight at 71.96%. In terms of pod length, the longest pods were observed in the Cozia1 × IR1 × CH variant, measuring 10.67 cm, which is 13% longer than the pods of the Cozia3 × IR1 × UF variant, measuring 9.24 cm. The widest pods were produced by the Cozia3 × IR2 × CH variant, with a width of 20.17 mm, 12% greater than the Cozia2 × IR1 × OR variant, which measured 17.80 mm.

Table 5. The influence of genotype × irrigation × fertilisation on the characteristics of runner bean pods.

Treatment	Pods per Plant	Seeds per Pod	Seed Weight Percentage (%)	Pericarp Weight Percentage (%)	Pods Length (cm)	Pods Width (mm)
Cozia1 × IR1 × OR	30.27 ± 2.71 c÷g	2.20 ± 0.03 d÷g	71.96 ± 0.28 e	28.04 ± 0.28 a	10.04 ± 0.06 bc	17.95 ± 0.13 efg
Cozia1 × IR2 × OR	27.58 ± 2.75 efg	2.39 ± 0.01 abc	76.04 ± 0.61 ab	23.96 ± 0.61 de	10.40 ± 0.05 ab	17.86 ± 0.14 fg
Cozia1 × IR1 × CH	30.79 ± 1.43 c÷f	2.41 ± 0.01 ab	75.14 ± 0.40 abc	24.86 ± 0.40 cde	10.67 ± 0.04 a	18.57 ± 0.41 b÷g
Cozia1 × IR2 × CH	29.01 ± 0.84 d÷g	2.28 ± 0.03 b÷e	72.69 ± 0.34 de	27.31 ± 0.34 ab	10.04 ± 0.09 bc	18.42 ± 0.09 b÷g
Cozia1 × IR1 × UF	31.28 ± 2.14 cde	2.28 ± 0.01 b÷e	76.06 ± 0.49 ab	23.94 ± 0.49 de	9.89 ± 0.17 bcd	17.97 ± 0.18 d÷g
Cozia1 × IR2 × UF	29.41 ± 1.37 d÷g	2.26 ± 0.01 c÷f	72.36 ± 0.30 de	27.64 ± 0.30 ab	9.94 ± 0.07 bc	18.35 ± 0.14 b÷g
Cozia2 × IR1 × OR	32.85 ± 1.31 bcd	2.33 ± 0.04 a÷d	76.77 ± 0.96 a	23.23 ± 0.96 e	9.61 ± 0.05 c÷f	17.80 ± 0.55 g
Cozia2 × IR2 × OR	36.02 ± 1.38 b	2.36 ± 0.06 abc	75.62 ± 0.87 ab	24.38 ± 0.87 de	10.01 ± 0.11 bc	18.21 ± 0.02 c÷g
Cozia2 × IR1 × CH	25.83 ± 0.38 g	2.43 ± 0.02 a	76.11 ± 0.47 ab	23.89 ± 0.47 de	9.84 ± 0.11 cde	18.46 ± 0.11 b÷g
Cozia2 × IR2 × CH	48.13 ± 0.95 a	2.18 ± 0.01 efg	75.35 ± 0.52 abc	24.65 ± 0.52 cde	9.39 ± 0.08 def	18.51 ± 0.14 b÷g
Cozia2 × IR1 × UF	29.94 ± 0.56 c÷g	2.10 ± 0.02 g	75.02 ± 0.20 abc	24.98 ± 0.20 cde	9.35 ± 0.05 ef	18.63 ± 0.11 b÷g
Cozia2 × IR2 × UF	27.00 ± 0.99 efg	2.38 ± 0.02 abc	76.74 ± 0.69 a	23.26 ± 0.69 e	10.00 ± 0.08 bc	19.38 ± 0.14 ab
Cozia3 × IR1 × OR	30.42 ± 0.55 c÷g	2.31 ± 0.02 a÷e	74.09 ± 0.15 bcd	25.91 ± 0.15 bcd	9.86 ± 0.03 cd	18.89 ± 0.30 b÷f
Cozia3 × IR2 × OR	36.24 ± 0.83 b	2.30 ± 0.01 a÷e	75.89 ± 0.16 ab	24.11 ± 0.16 de	9.83 ± 0.05 cde	18.95 ± 0.18 b÷e
Cozia3 × IR1 × CH	36.42 ± 1.07 b	2.34 ± 0.01 abc	76.71 ± 0.32 a	23.29 ± 0.32 e	9.76 ± 0.07 cde	19.15 ± 0.24 bc
Cozia3 × IR2 × CH	32.92 ± 1.33 bcd	2.26 ± 0.04 c÷f	72.18 ± 1.35 de	27.82 ± 1.35 ab	9.89 ± 0.08 bcd	20.17 ± 0.30 a
Cozia3 × IR1 × UF	26.33 ± 1.83 fg	2.14 ± 0.14 fg	73.60 ± 0.59 cde	26.40 ± 0.59 abc	9.24 ± 0.57 f	18.20 ± 0.90 c÷g
Cozia3 × IR2 × UF	34.72 ± 0.68 bc	2.43 ± 0.02 a	73.46 ± 0.87 cde	26.54 ± 0.87 abc	9.92 ± 0.05 bc	19.02 ± 0.12 bcd

The values are presented as mean ± standard error of individual replicates. Within each column, the different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, where 'a' represents the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1—2000 m³·ha^{−1} irrigation; IR2—2500 m³·ha^{−1} irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized.

Regarding the seed morphological and yield traits of runner beans, the three-way interaction between genotype, irrigation, and fertilisation showed that the Cozia3 × IR1 × UF variant produced beans with the lowest measurements for length (19.24 mm, −11.4%), width (12.55 mm, −11.7%), and thickness (7.76 mm, −15.1%). In contrast, the highest measurements were recorded for bean length in Cozia1 × IR1 × UF (21.72 mm), grain width in Cozia2 × IR2 × UF (14.21 mm), and bean thickness in Cozia2 × IR2 × OR (9.14 mm). The maximum TGW was observed in Cozia2 × IR2 × UF (1525.19 g), representing a 13% increase compared to Cozia2 × IR1 × OR (1323.20 g). The highest yield was obtained from

the Cozia2 $\times$ IR2 $\times$ CH variant, with 3427.60 kg·ha⁻¹, which is 36% higher than those recorded for Cozia1 $\times$ IR1 $\times$ OR (2193.43 kg·ha⁻¹) (Table 6).

Table 6. The influence of genotype $\times$ irrigation $\times$ fertilisation on the seed morphological and yield traits of runner bean.

Treatment	Beans Length (mm)	Beans Width (mm)	Beans Thickness (mm)	TGW (g)	Grain Yield (kg·ha ⁻¹)
Cozia1 $\times$ IR1 $\times$ OR	20.87 $\pm$ 0.02 abc	12.71 $\pm$ 0.05 h	8.74 $\pm$ 0.14 abc	1424.81 $\pm$ 34.81 a÷d	2193.43 $\pm$ 70.42 i
Cozia1 $\times$ IR2 $\times$ OR	21.35 $\pm$ 0.04 ab	13.06 $\pm$ 0.08 d÷h	8.65 $\pm$ 0.06 a÷e	1485.29 $\pm$ 4.24 ab	2976.34 $\pm$ 71.44 bcd
Cozia1 $\times$ IR1 $\times$ CH	21.07 $\pm$ 0.15 abc	13.48 $\pm$ 0.13 b÷g	8.67 $\pm$ 0.08 a÷d	1524.20 $\pm$ 21.83 a	2758.95 $\pm$ 118.60 def
Cozia1 $\times$ IR2 $\times$ CH	20.30 $\pm$ 0.14 bcd	13.01 $\pm$ 0.01 e÷h	8.70 $\pm$ 0.08 abc	1382.78 $\pm$ 15.11 bcd	2254.53 $\pm$ 41.62 hi
Cozia1 $\times$ IR1 $\times$ UF	21.72 $\pm$ 1.14 a	12.96 $\pm$ 0.08 fgh	8.45 $\pm$ 0.13 b÷e	1400.44 $\pm$ 36.29 bcd	2632.00 $\pm$ 159.87 d÷h
Cozia1 $\times$ IR2 $\times$ UF	20.74 $\pm$ 0.18 abc	12.93 $\pm$ 0.04 gh	8.95 $\pm$ 0.31 ab	1448.90 $\pm$ 16.93 abc	2218.33 $\pm$ 31.51 i
Cozia2 $\times$ IR1 $\times$ OR	19.96 $\pm$ 0.15 cd	13.30 $\pm$ 0.05 c÷g	8.27 $\pm$ 0.10 c÷g	1323.20 $\pm$ 13.92 d	2688.80 $\pm$ 86.01 d÷g
Cozia2 $\times$ IR2 $\times$ OR	19.90 $\pm$ 0.14 cd	13.43 $\pm$ 0.05 c÷g	9.14 $\pm$ 0.36 a	1382.43 $\pm$ 20.77 bcd	2802.72 $\pm$ 107.69 c÷f
Cozia2 $\times$ IR1 $\times$ CH	19.83 $\pm$ 0.10 cd	13.61 $\pm$ 0.09 bcd	8.91 $\pm$ 0.31 ab	1360.35 $\pm$ 33.29 cd	2316.76 $\pm$ 17.91 ghi
Cozia2 $\times$ IR2 $\times$ CH	20.01 $\pm$ 0.13 cd	13.56 $\pm$ 0.06 b÷e	8.65 $\pm$ 0.04 a÷e	1404.95 $\pm$ 22.37 bcd	3427.60 $\pm$ 121.10 a
Cozia2 $\times$ IR1 $\times$ UF	20.08 $\pm$ 0.20 bcd	13.73 $\pm$ 0.02 abc	8.30 $\pm$ 0.06 c÷g	1480.92 $\pm$ 24.00 ab	2520.31 $\pm$ 42.84 e÷i
Cozia2 $\times$ IR2 $\times$ UF	20.52 $\pm$ 0.22 a÷d	14.21 $\pm$ 0.04 a	8.40 $\pm$ 0.11 b÷f	1525.19 $\pm$ 57.11 a	2289.18 $\pm$ 100.44 ghi
Cozia3 $\times$ IR1 $\times$ OR	20.16 $\pm$ 0.17 bcd	13.41 $\pm$ 0.12 c÷g	8.05 $\pm$ 0.06 efg	1374.30 $\pm$ 33.22 cd	2983.48 $\pm$ 41.05 bcd
Cozia3 $\times$ IR2 $\times$ OR	20.14 $\pm$ 0.01 bcd	13.81 $\pm$ 0.02 abc	8.07 $\pm$ 0.04 efg	1444.20 $\pm$ 7.89 abc	3202.23 $\pm$ 130.76 abc
Cozia3 $\times$ IR1 $\times$ CH	20.11 $\pm$ 0.26 bcd	13.52 $\pm$ 0.11 b÷f	7.84 $\pm$ 0.05 fg	1403.26 $\pm$ 45.89 bcd	3327.24 $\pm$ 136.65 ab
Cozia3 $\times$ IR2 $\times$ CH	20.04 $\pm$ 0.07 bcd	14.04 $\pm$ 0.08 ab	8.08 $\pm$ 0.16 d÷g	1380.58 $\pm$ 59.78 bcd	2933.51 $\pm$ 258.96 bcd
Cozia3 $\times$ IR1 $\times$ UF	19.24 $\pm$ 0.99 d	12.55 $\pm$ 0.68 h	7.76 $\pm$ 0.38 g	1379.51 $\pm$ 31.68 bcd	2414.49 $\pm$ 282.39 f÷i
Cozia3 $\times$ IR2 $\times$ UF	19.93 $\pm$ 0.14 cd	13.34 $\pm$ 0.03 c÷g	8.09 $\pm$ 0.04 d÷g	1350.32 $\pm$ 12.28 cd	2849.90 $\pm$ 37.39 cde

The values are presented as mean $\pm$ standard error of individual replicates. Within each column, the different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, where 'a' represents the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1—2000 m³·ha⁻¹ irrigation; IR2—2500 m³·ha⁻¹ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TGW—thousand-grain weight.

3.3. Influence of Experimental Factors on Biochemical Indicators

The quality of runner bean seeds showed significant variation in total polyphenol content (TPC) and antioxidant capacity depending on genotype, while only DPPH was affected by fertilization. In contrast, irrigation had no notable impact on TPC, DPPH, or ABTS (Table 7). Among cultivars, Cozia3 exhibited the highest TPC at 0.37 mg GAE·100 g⁻¹ d.w., a value significantly higher than Cozia1 (0.32 mg GAE·100 g⁻¹ d.w.) and Cozia2 (0.31 mg GAE·100 g⁻¹ d.w.). Cozia3 also showed the highest DPPH activity (0.13 mmol TE·100 g⁻¹ d.w.), but the lowest ABTS (0.26 mmol TE·100 g⁻¹ d.w.). Regarding fertilization, the data indicated that chemical fertilization resulted in the highest TPC (0.35 mg GAE·100 g⁻¹ d.w.) and DPPH activity (0.14 mmol TE·100 g⁻¹ d.w.), while the unfertilized variant reached the lowest values (0.32 mg GAE·100 g⁻¹ d.w. and 0.12 mmol TE·100 g⁻¹ d.w.).

The two-way interactions between genotype, irrigation, and fertilisation significantly affected the biochemical properties of runner bean seeds. Only ABTS activity showed no significant differences in the genotype $\times$ fertilisation and irrigation $\times$ fertilisation interactions, as detailed in Table 8. While irrigation alone did not cause notable changes in biochemical traits, its interaction with genotype led to significant variations. Specifically, higher irrigation levels increased TPC in Cozia1 (0.39 mg GAE·100 g⁻¹ d.w.) but decreased DPPH activity in Cozia2. Additionally, although increased irrigation improved TPC in Cozia1, it reduced TPC levels in the other two cultivars. Furthermore, in the irrigation $\times$ fertilisation interaction, the highest TPC values were observed in the IR1 $\times$ CH and IR2 $\times$ OR variants, which were significantly higher than other treatments. Conversely, the IR2 $\times$ OR combination resulted in the lowest DPPH content. Under the cultivar $\times$ fertilisation interaction, the Cozia3 $\times$ OR variant registered the highest TPC value (0.44 mg GAE·100 g⁻¹ d.w.), which was 36% higher than in Cozia1 $\times$ OR and Cozia1 $\times$ UF, variants with the lowest TPC. Antioxidant activity measured by the DPPH assay was highest in the Cozia3 $\times$ CH variant (0.16 mmol TE·100 g⁻¹ d.w.), showing a 31% difference compared to the lowest value recorded in Cozia1 $\times$ UF (0.11 mmol TE·100 g⁻¹ d.w.). The ABTS assay, in contrast,

showed no statistically significant variation across treatments, with differences limited to a 10% range.

Table 7. The individual influences of genotype, irrigation, and fertilization on the biochemical characteristics of runner bean beans.

Treatment	TPC (mg GAE·100 g ⁻¹ d.w.)	DPPH (mmol TE·100 g ⁻¹ d.w.)	ABTS (mmol TE·100 g ⁻¹ d.w.)
Cozia1	0.32 ± 0.00 b	0.12 ± 0.00 b	0.28 ± 0.00
Cozia2	0.31 ± 0.01 b	0.12 ± 0.00 ab	0.27 ± 0.01
Cozia3	0.37 ± 0.01 a	0.13 ± 0.00 a	0.26 ± 0.00
Signification	*	*	ns
IR1	0.33 ± 0.00	0.13 ± 0.00	0.27 ± 0.00
IR2	0.34 ± 0.01	0.12 ± 0.00	0.27 ± 0.00
Signification	ns	ns	ns
OR	0.33 ± 0.01	0.12 ± 0.00 b	0.27 ± 0.01
CH	0.35 ± 0.01	0.14 ± 0.01 a	0.26 ± 0.00
UF	0.32 ± 0.01	0.12 ± 0.00 b	0.27 ± 0.01
Signification	ns	*	ns

The values are presented as mean ± standard error of individual replicates. Within each column, and factor group: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m³·ha⁻¹ irrigation; IR2—2500 m³·ha⁻¹ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TPC—total polyphenol content; DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

The three-way interactions among genotype, irrigation, and fertilisation indicated that the combination of Cozia1 × IR1 × CH recorded the highest TPC, at 0.47 mg GAE·100 g⁻¹ d.w. This value was not significantly different from those of Cozia3 × IR1 × OR and Cozia3 × IR2 × OR, but it was significantly higher than those observed in the other experimental variants. However, under the influence of IR1 × OR and IR1 × UF, the Cozia1 cultivar exhibited the lowest TPC values, with 0.17 mg GAE·100 g⁻¹ d.w. and 0.21 mg GAE·100 g⁻¹ d.w., respectively, highlighting a strong interaction effect between fertilization type and genotype under the same irrigation regime.

Regarding antioxidant activity, the three-way interaction among factors showed that the values determined by the DPPH assay varied by 47%, ranging from 0.09 mmol TE·100 g⁻¹ d.w. in the Cozia2 × IR2 × OR variant to 0.17 mmol TE·100 g⁻¹ d.w. in the Cozia3 × IR2 × CH variant. The ABTS assay revealed the highest antioxidant activity in the Cozia1 × IR2 × UF variant, with a value of 0.31 mmol TE·100 g⁻¹ d.w., which was 23% higher than that of the Cozia2 × IR2 × UF variant (0.24 mmol TE·100 g⁻¹ d.w.). Statistically, the variation in antioxidant compound levels measured by the DPPH assay was notably greater than by the ABTS. The Cozia3 × IR2 × CH variant, with the highest DPPH antioxidant content, was significantly higher than all other variants, except when compared with Cozia3 × IR1 × CH (Table 9). In contrast, regarding the ABTS assay, the Cozia2 × IR2 × UF variant showed significantly lower antioxidant activity compared only to Cozia1 × IR1 × OR, Cozia1 × IR2 × UF, and Cozia2 × IR2 × OR.

Table 8. The influence of genotype $\times$ irrigation, genotype $\times$ fertilisation, and irrigation $\times$ fertilisation interactions on the biochemical characteristics of runner bean beans.

Treatment	TPC (mg GAE $\cdot$ 100 g $^{-1}$ d.w.)	DPPH (mmol TE $\cdot$ 100 g $^{-1}$ d.w.)	ABTS (mmol TE $\cdot$ 100 g $^{-1}$ d.w.)
Cozia1 $\times$ IR1	0.28 $\pm$ 0.00 c	0.11 $\pm$ 0.00 b	0.27 $\pm$ 0.00 ab
Cozia1 $\times$ IR2	0.36 $\pm$ 0.01 ab	0.13 $\pm$ 0.00 ab	0.28 $\pm$ 0.00 a
Cozia2 $\times$ IR1	0.33 $\pm$ 0.00 bc	0.13 $\pm$ 0.00 a	0.27 $\pm$ 0.00 ab
Cozia2 $\times$ IR2	0.30 $\pm$ 0.02 c	0.12 $\pm$ 0.01 b	0.26 $\pm$ 0.01 b
Cozia3 $\times$ IR1	0.39 $\pm$ 0.01 a	0.13 $\pm$ 0.00 a	0.27 $\pm$ 0.01 ab
Cozia3 $\times$ IR2	0.35 $\pm$ 0.01 ab	0.13 $\pm$ 0.00 a	0.26 $\pm$ 0.00 b
Signification	*	*	*
Cozia1 $\times$ OR	0.28 $\pm$ 0.00 d	0.13 $\pm$ 0.00 bc	0.27 $\pm$ 0.01
Cozia1 $\times$ CH	0.40 $\pm$ 0.01 ab	0.12 $\pm$ 0.00 bcd	0.27 $\pm$ 0.01
Cozia1 $\times$ UF	0.28 $\pm$ 0.00 d	0.11 $\pm$ 0.00 d	0.29 $\pm$ 0.01
Cozia2 $\times$ OR	0.30 $\pm$ 0.04 d	0.11 $\pm$ 0.00 cd	0.29 $\pm$ 0.02
Cozia2 $\times$ CH	0.36 $\pm$ 0.01 bc	0.14 $\pm$ 0.01 b	0.26 $\pm$ 0.00
Cozia2 $\times$ UF	0.31 $\pm$ 0.01 cd	0.12 $\pm$ 0.01 bcd	0.26 $\pm$ 0.01
Cozia3 $\times$ OR	0.44 $\pm$ 0.02 a	0.12 $\pm$ 0.00 cd	0.26 $\pm$ 0.00
Cozia3 $\times$ CH	0.29 $\pm$ 0.00 d	0.16 $\pm$ 0.01 a	0.26 $\pm$ 0.01
Cozia3 $\times$ UF	0.38 $\pm$ 0.02 b	0.12 $\pm$ 0.00 bcd	0.27 $\pm$ 0.00
Signification	*	*	ns
IR1 $\times$ OR	0.30 $\pm$ 0.00 c	0.13 $\pm$ 0.00 ab	0.28 $\pm$ 0.01
IR1 $\times$ CH	0.39 $\pm$ 0.00 a	0.13 $\pm$ 0.00 ab	0.26 $\pm$ 0.00
IR1 $\times$ UF	0.31 $\pm$ 0.01 c	0.12 $\pm$ 0.00 bc	0.28 $\pm$ 0.01
IR2 $\times$ OR	0.37 $\pm$ 0.03 ab	0.11 $\pm$ 0.00 c	0.27 $\pm$ 0.01
IR2 $\times$ CH	0.31 $\pm$ 0.01 c	0.15 $\pm$ 0.01 a	0.27 $\pm$ 0.01
IR2 $\times$ UF	0.33 $\pm$ 0.00 bc	0.12 $\pm$ 0.01 bc	0.27 $\pm$ 0.00
Signification	*	*	ns

The values are presented as mean $\pm$ standard error of individual replicates. Within each column, and for each combination of two factors: ns—statistically insignificant differences; *—statistically significant differences at $p \leq 0.05$ according to Duncan's test. The different letters indicate statistical differences between variants, with 'a' representing the highest values. Cozia1, Cozia2, Cozia3 are the beans cultivars; IR1—2000 m 3 ·ha $^{-1}$ irrigation; IR2—2500 m 3 ·ha $^{-1}$ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TPC—total polyphenol content; DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

Table 9. The influence of genotype $\times$ irrigation $\times$ fertilisation on the biochemical characteristics of runner bean beans.

Treatment	TPC (mg GAE $\cdot$ 100 g $^{-1}$ d.w.)	DPPH (mmol TE $\cdot$ 100 g $^{-1}$ d.w.)	ABTS (mmol TE $\cdot$ 100 g $^{-1}$ d.w.)
Cozia1 $\times$ IR1 $\times$ OR	0.17 $\pm$ 0.00 i	0.14 $\pm$ 0.01 bcd	0.29 $\pm$ 0.01 abc
Cozia1 $\times$ IR2 $\times$ OR	0.39 $\pm$ 0.01 bcd	0.12 $\pm$ 0.01 c÷g	0.25 $\pm$ 0.01 cd
Cozia1 $\times$ IR1 $\times$ CH	0.47 $\pm$ 0.01 a	0.11 $\pm$ 0.00 fgh	0.27 $\pm$ 0.00 bcd
Cozia1 $\times$ IR2 $\times$ CH	0.34 $\pm$ 0.03 def	0.14 $\pm$ 0.01 bcd	0.28 $\pm$ 0.01 a÷d
Cozia1 $\times$ IR1 $\times$ UF	0.21 $\pm$ 0.00 hi	0.10 $\pm$ 0.00 gh	0.27 $\pm$ 0.01 bcd
Cozia1 $\times$ IR2 $\times$ UF	0.35 $\pm$ 0.00 de	0.12 $\pm$ 0.01 c÷f	0.31 $\pm$ 0.01 a
Cozia2 $\times$ IR1 $\times$ OR	0.28 $\pm$ 0.00 fgh	0.14 $\pm$ 0.01 bc	0.28 $\pm$ 0.02 a÷d
Cozia2 $\times$ IR2 $\times$ OR	0.28 $\pm$ 0.03 fgh	0.09 $\pm$ 0.00 h	0.30 $\pm$ 0.02 ab
Cozia2 $\times$ IR1 $\times$ CH	0.37 $\pm$ 0.00 cd	0.13 $\pm$ 0.01 b÷e	0.26 $\pm$ 0.01 bcd
Cozia2 $\times$ IR2 $\times$ CH	0.35 $\pm$ 0.02 d	0.14 $\pm$ 0.01 bc	0.25 $\pm$ 0.00 cd
Cozia2 $\times$ IR1 $\times$ UF	0.33 $\pm$ 0.00 def	0.12 $\pm$ 0.00 c÷f	0.28 $\pm$ 0.02 a÷d
Cozia2 $\times$ IR2 $\times$ UF	0.28 $\pm$ 0.01 efg	0.12 $\pm$ 0.01 c÷f	0.24 $\pm$ 0.01 d
Cozia3 $\times$ IR1 $\times$ OR	0.45 $\pm$ 0.01 ab	0.12 $\pm$ 0.00 c÷f	0.26 $\pm$ 0.01 bcd

Table 9. Cont.

Treatment	TPC (mg GAE·100 g ⁻¹ d.w.)	DPPH (mmol TE·100 g ⁻¹ d.w.)	ABTS (mmol TE·100 g ⁻¹ d.w.)
Cozia3 × IR2 × OR	0.43 ± 0.05 abc	0.12 ± 0.00 d÷g	0.26 ± 0.01 bcd
Cozia3 × IR1 × CH	0.34 ± 0.01 def	0.15 ± 0.00 ab	0.25 ± 0.00 cd
Cozia3 × IR2 × CH	0.24 ± 0.02 gh	0.17 ± 0.01 a	0.27 ± 0.02 bcd
Cozia3 × IR1 × UF	0.39 ± 0.05 bcd	0.13 ± 0.01 cde	0.28 ± 0.00 a÷d
Cozia3 × IR2 × UF	0.37 ± 0.00 cd	0.11 ± 0.00 efg	0.25 ± 0.01 cd

The values are presented as mean ± standard error of individual replicates. Within each column, the different letters represent statistical differences between variants at $p \leq 0.05$ according to Duncan's test, where 'a' represents the highest values. Cozia1, Cozia2, Cozia3 are beans cultivars; IR1—2000 m³·ha⁻¹ irrigation; IR2—2500 m³·ha⁻¹ irrigation; OR—organic fertilization; CH—chemical fertilization; UF—unfertilized; TPC—total polyphenol content; DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

3.4. Multivariate Relationships Among Traits

The multivariate analysis, combining Principal Component Analysis (PCA) and Pearson correlation, provided valuable insights into the underlying structure and interrelationships among traits across various combinations of Cozia bean cultivars, irrigation regimes, and fertilization treatments. PCA conducted on the complete dataset showed that seven of the sixteen principal components had eigenvalues greater than 1, indicating significant dimensions of trait variability. The first three components explained a cumulative 60.64% of the total variance, with PC1 accounting for 26.34% (eigenvalue: 4.21), PC2 for 21.53% (eigenvalue: 3.45), and PC3 for 12.77% (eigenvalue: 2.04), as presented in Table 10 and illustrated in Figure 9.

Table 10. Eigenvalues of the correlation matrix showing the affinities of the physiological, biometric, and biochemical traits of Cozia cultivars under fertilization treatments and irrigation regimes to PCs.

PC	Eigenvalue	Percentage of Variance (%)	Cumulative Percentage of Variance (%)
1	4.214	26.34	26.34
2	3.445	21.53	47.87
3	2.044	12.77	60.64
4	1.397	8.73	69.37
5	1.197	7.48	76.85
6	1.114	6.96	83.81
7	0.973	6.08	89.9
8	0.506	3.16	93.06
9	0.446	2.79	95.84
10	0.300	1.87	97.72
11	0.155	0.97	98.69
12	0.117	0.73	99.42
13	0.064	0.4	99.82
14	0.026	0.16	99.99
15	0.002	0.01	100

According to Table S1, the main positive contributors to PC1 were assimilation rate (0.292), CCI (0.376), number of seeds per pod (0.315), and seed weight percent (0.376), while pericarp weight percentage (−0.376) and ABTS (−0.307) were the most substantial negative contributors. This pattern suggests that PC1 captures a dimension related to plant productivity and photosynthetic efficiency. In contrast, pericarp weight percentage and ABTS, which exhibited a high negative loading on PC1, suggest a strong and inverse contribution to the component primarily associated with photosynthetic efficiency and yield performance. Thus, the Cozia cultivars influenced by irrigation and fertilisation

regimes located on the negative side of PC1 tend to show higher pericarp biomass and antioxidant activity, often at the detriment of traits related to yield and photosynthetic efficiency. Regarding PC2, it exhibited strong positive loadings for bean thickness (0.368), pod length (0.311), bean length (0.325), and ABTS antioxidant activity (0.279). This component appears to capture variation primarily associated with pod and seed morphology, as well as antioxidant potential. These associations suggest that PC2 reflects a combination of morphological and biochemical traits, potentially influenced by genetic differences among cultivars and/or interactions between genotype, irrigation regime, and fertilization treatments. For PC3, the main positive contributors were pod width (0.455), pod length (0.305), TGW (0.335), and pericarp weight percentage (0.312), further highlighting the emphasis of this component on size-related attributes.

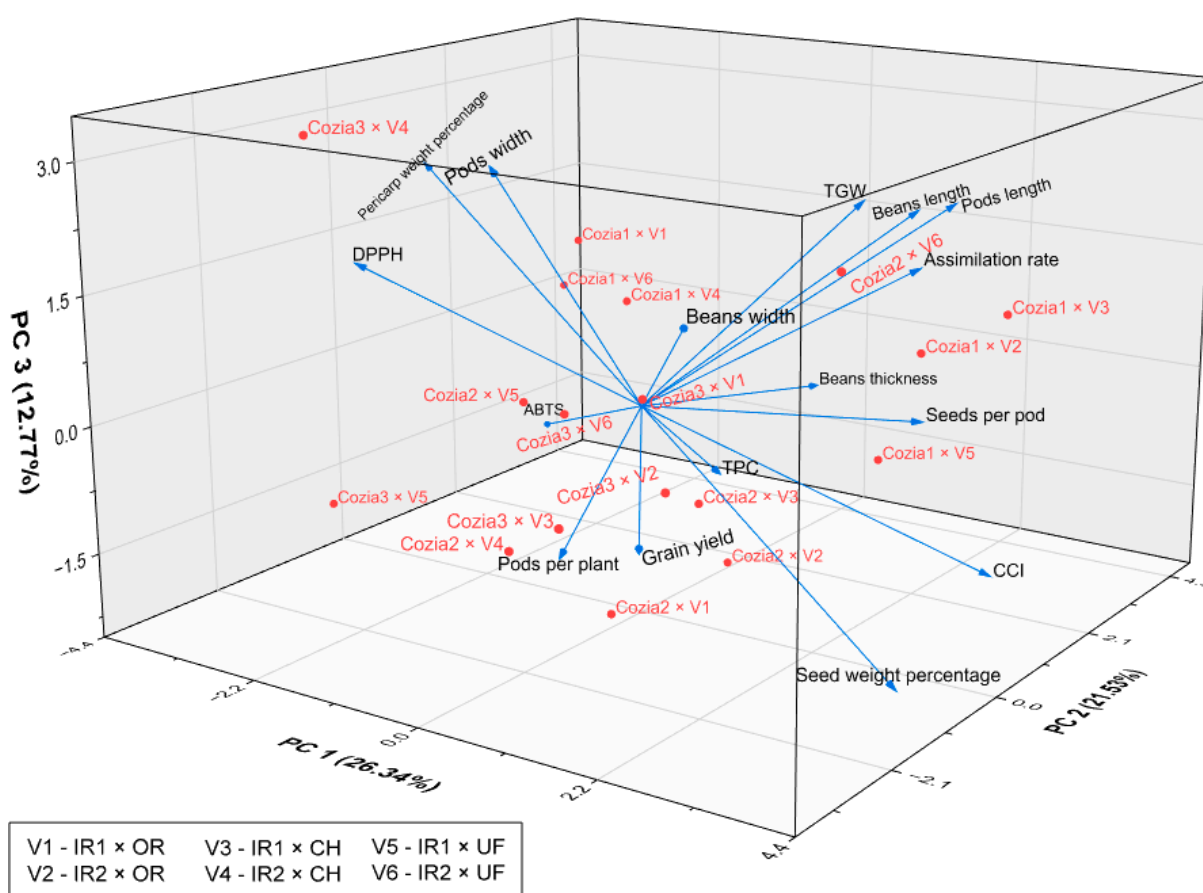


Figure 9. Principal component analysis score plot showing the variation in physiological, biometric, and biochemical traits of Cozia cultivars under fertilization treatments and irrigation norms. CCI—chlorophyll content index; TGW—thousand-grain weight; TPC—total polyphenol content; DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

In summary, PCA revealed that the main sources of variation in the dataset are related to traits involved in productivity, morphology, and antioxidant capacity, which are influenced by the interaction of genotype, water availability, and nutrient management.

Furthermore, the Pearson correlation analysis reveals several strong associations between morphological, physiological, and biochemical traits across cultivars, irrigation norms, and fertilization treatment interactions (Figure 10). The seeds' weight percentage, chlorophyll content index (CCI), assimilation rate, grain yield, and seeds per pod are positively correlated among themselves, with low to moderate correlations (e.g., assimilation

rate vs. seeds per pod: $r = 0.35$; CCI vs. grain yield: $r = 0.33$). Bean width is weakly negatively correlated with bean thickness ($r = -0.13$) and bean length ($r = -0.14$), while it is strongly positively correlated with pod width ($r = 0.74$). The seeds' weight percentage and grain yield ($r = 0.37$) indicate that heavier seeds contribute significantly to total grain yield. As expected, pericarp weight percentage was strongly negatively correlated with seed weight percentage ($r = -1.00$), reflecting their complementary relationship within total pod mass. Additionally, the pericarp weight percentage exhibits a negative correlation with grain yield ($r = -0.37$), indicating that higher pericarp content may limit harvestable seed yield. TGW correlates moderately positively with bean length ($r = 0.50$) but has a low negative correlation with grain yield ($r = -0.10$).

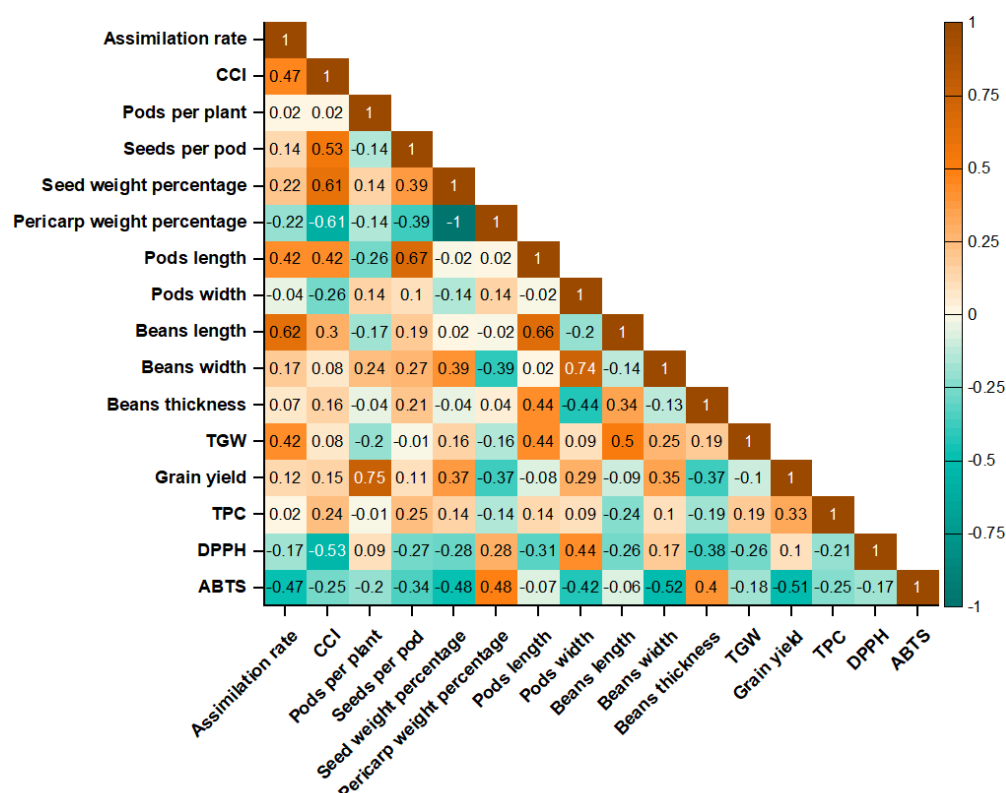


Figure 10. Heatmap of Pearson correlation coefficients among physiological, biometric, and biochemical traits of Cozia cultivars under fertilization treatments and irrigation norms. CCI—chlorophyll content index; TGW—thousand-grain weight; TPC—total polyphenol content; DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

A notable pattern emerged between photosynthetic traits and antioxidant capacity: both assimilation rate and CCI were negatively correlated with DPPH and ABTS activities (r ranging from -0.17 to -0.53), suggesting that increased photosynthetic performance may be linked to lower antioxidant levels. Furthermore, the number of seeds per pod showed a positive correlation with both the assimilation rate ($r = 0.35$) and CCI ($r = 0.30$), reinforcing the connection between photosynthetic efficiency and reproductive success. The weak negative correlation between ABTS and DPPH ($r = -0.17$) further indicates that the two antioxidant assays only partially measure the same aspects of antioxidant potential in the studied samples. Likewise, biometrical traits of pods and seeds, such as pod length, pod width, seed size, and seed weight, also showed negative correlations with both antioxidant assays. These findings suggest a possible trade-off between yield-related morphological traits and biochemical quality indicators, where genotypes or treatments that promote higher productivity may exhibit lower antioxidant potential.

4. Discussion

4.1. General Overview of Factor Effects

This study demonstrated that cultivar, irrigation regime, and fertilization strategy influenced the physiological, biometric, and biochemical traits of runner beans, both independently and interactively. The three-way ANOVA (Table S2) showed that the individual effect of genotype was significant for nearly all parameters considered, with the exception of the chlorophyll content index (CCI) and the number of seeds per pod. By contrast, fertilization had a non-significant effect only on CCI and bean length, while irrigation did not significantly affect assimilation rate, bean length, thousand grain weight (TGW), total phenolic content (TPC), DPPH, and ABTS. The interaction between genotype and irrigation was significant for most of the analysed traits, except number of seeds per pod, seed weight percentage, pericarp weight percentage, bean thickness, and ABTS. In contrast, the interaction between genotype and fertilization was non-significant only for ABTS. The interaction between irrigation and fertilization significantly affected most analysed characteristics. However, the three-way interaction was significant for the majority of the assessed traits, with pod width being the only exception.

4.2. Effects of Experimental Factors on Physiological Indicators

The significant variation in assimilation rate, observed in this study under the same environmental conditions but differing according to genotype, highlighted the role of genetic factors in determining the physiological and productive potential of runner bean, a variation consistently documented in the literature, as reported by Álvarez-Iglesias et al. [58] in six maize inbred lines, by Huo and Guo [59] in four chestnut cultivars, as well as by Gong et al. [60] and Ukwu et al. [61] in various mung bean genotypes. The differences among genotypes may be attributed to variations in leaf morphology, chlorophyll content, photosynthetic capacity, and nutrient-use efficiency. In particular, differences in nutrient-use efficiency, as reported in the literature [62,63] were also highlighted in this study through the significant interaction between genotype and fertilization regime. The preference of certain cultivars for specific types of fertilisers was also reported by Jawad Moharam Al-Bayati et al. [64] in their study on pea. The local cultivar exhibited higher chlorophyll content under organic fertilisation with poultry manure, whereas the Holland Ian cultivar responded better to chemical fertilisation. In another study, it was found that the basil cultivar Aromat de Buzău showed a higher CO₂ assimilation rate under chemical fertilisation, whereas the cultivars Macedon, Cuişoare, and Serafim performed better under organic fertilisation [65].

The increase in photosynthetic assimilation rate of runner beans with organic fertilization, as shown in this study, compared to both chemically fertilized and unfertilized options, is probably due to better soil structure, increased microbial activity, and sustained nutrient release associated with organic amendments [31,62]. Unlike chemical fertilization, which often leads to rapid but short-term nutrient availability, organic inputs contribute to a more balanced and prolonged nutrient supply, promoting better root development and more efficient assimilation of essential elements such as nitrogen and phosphorus. In contrast, the higher CCI values in plants treated with chemical fertilizers are due to the immediate availability of essential nutrients, especially nitrogen which plays a crucial role in the formation of photosynthetic pigments. Chemical fertilizers, being highly soluble, provide nitrogen in readily available forms, leading to rapid chlorophyll accumulation, especially in the early vegetative stages [66]. However, organic fertilizers release nutrients more gradually because soil microorganisms must mineralize nitrogen before plants can absorb it. This slow nutrient release may reduce chlorophyll accumulation but can support extended pigment synthesis, particularly in later growth stages [67,68]. The reduced photo-

synthetic efficiency in unfertilized variants is likely due to nutrient limitations and lower soil biological activity [67,68]. Similarly, Precupeanu et al. [69] found a significantly higher assimilation rate in organically fertilized perennial wall rocket compared to the chemically fertilized and unfertilized treatments.

The interaction between genotype and irrigation regime showed that each genotype uniquely responds to water availability. Cozia1, under lower irrigation (IR1), had a higher photosynthetic assimilation rate and increased chlorophyll accumulation, indicating efficient adaptation to limited water. In contrast, Cozia2 exhibited even higher physiological responses. Cozia3 maintained consistent responses across treatments, suggesting a less sensitive adaptation to water variations. These results indicate that Cozia1 prioritizes physiological processes like photosynthesis under moderate irrigation, while Cozia3 may use alternative mechanisms for performance. This genotype-specific behaviour suggests that traits like water use efficiency and stomatal regulation play key roles in mediating responses to irrigation, as also noted in previous studies [70,71]. Similarly, Papathanasiou et al. [72] observed genotype-dependent variation in chlorophyll content in *Phaseolus vulgaris* L., which was not significantly affected by irrigation treatments, further supporting the genotype-driven nature of physiological adaptation.

The significant effect of the interaction between irrigation regime and fertilisation on physiological responses highlighted the complex influence of water and nutrient availability. As Cheng et al. [73] explain, water is essential for nutrient uptake, as nutrients must be dissolved in water to be absorbed by plants. Therefore, the low photosynthesis in IR1 × CH may be due to limited nutrient solubilisation caused by insufficient water, despite higher chlorophyll levels, which may reflect a compensatory response. Conversely, the IR1 × OR combination likely provided a balanced nutrient release and optimal soil conditions, thereby supporting higher photosynthetic activity.

Furthermore, the results of the three-way interaction among genotype, irrigation, and fertilization highlighted the importance of developing cultivar-specific strategies for irrigation and fertilization to enhance physiological performance. For instance, Cozia1 is sensitive to high irrigation levels when no fertilization is applied, while Cozia2 shows better adaptation under these conditions. In contrast, Cozia3 is the most vulnerable to the combined limitations of water and nutrients. Overall, the assimilation rate is more significantly impacted by these interactions than the CCI.

4.3. Effects of Experimental Factors on Biometric Indicators

With regard to biometric indicators, the results of this study support previous research highlighting the importance of genetic variability in shaping morphological and yield-related traits. [20,74–76]. Among the cultivars, Cozia2 exhibited the highest number of pods per plant and seed weight percentage, reflecting strong reproductive vigour compared to the other two cultivars. Cozia1 showed superior pod length and pericarp weight percentage, while Cozia3 had the largest pod width. In contrast, the irrigation regime induced significant variation in the number of pods per plant, seed weight percentage, and pericarp weight percentage. These results highlight the critical role of water availability during key developmental stages such as pod formation and seed filling. Increased irrigation probably enhances assimilate transport and allocation to reproductive structures, thereby improving these yield-related parameters. This finding aligns with results from other studies, which have reported improved reproductive efficiency and seed development under optimal water supply conditions [77–79]. Fertilisation had a significant impact on the number of pods per plant, pod width, and grain yield, indicating that nutrient availability plays key roles in shaping pod and seed development [31,80].

The two-way interactions between factors suggest that the cultivar's adaptability and performance are strongly influenced by how they interact with water and nutrient availability. Even though the interaction between genotype and irrigation did not generally lead to significant differences in the biometric traits analysed, there were some cultivar-specific responses. Notably, Cozia1 showed an inverse relationship with increasing irrigation volume, with most biometric parameters decreasing with increasing water intake. Cozia2 and Cozia3 showed a positive response to increased irrigation, leading to improvements in several yield-related traits. These contrasting responses suggest variations in water use efficiency and adaptive strategies among the cultivars. Similar results were reported by El-Noemani et al. [28], who observed differential responses to irrigation between the Bronco and Paulista bean varieties, further supporting the idea that water availability interacts differently with specific genotypes. Furthermore, genotype $\times$ fertilization interactions emphasize that the use of one type of fertilization cannot be generalized to all cultivars but must be aligned with their distinct nutritional requirements. The variability observed between different varieties in terms of responses to fertilization suggests that yield optimization requires the adaptation of fertilization practices to meet the specific requirements of each genotype.

The results of this study also showed that achieving optimal productivity requires aligning fertilisation strategies with irrigation levels to meet genotype-specific demands. For instance, in the IR2 $\times$ CH variant, the highest pod number, pericarp weight percentage, and pod width were recorded, whereas IR1 $\times$ CH yielded the most significant number of seeds per pod and the longest pods, highlighting different nutrient uptake dynamics under varying water availability. The poor performance observed under IR1 $\times$ UF emphasises the combined effect of water and nutrient limitations. Regarding bean traits, the IR2 $\times$ OR interaction improved seed length, thickness, and yield, while the lowest TGW and yield were recorded under IR1 $\times$ OR and IR2 $\times$ UF, respectively. These findings are consistent with results reported by Khlila et al. [81] in wheat cultivation, Dong et al. [82] in peanuts, or by Song et al. [83] in tomatoes, further supporting the genotype-specific nature of water–nutrient interactions.

The three-factor interaction demonstrated that morphological traits were variably affected by the interplay of genotype, fertilization, and irrigation. Cozia2 displayed heightened sensitivity, whereas Cozia1 and Cozia3 exhibited relatively stable and intermediate values for this trait regardless of fertilisation and irrigation variations. This underscores the necessity of implementing genotype-specific management strategies to enhance performance.

4.4. Effects of Experimental Factors on Biochemical Indicators

Variation in genotype, irrigation, and fertilisation regimes, as well as their interactions, had a significant impact on bean seed quality. The findings of this study align with the hypothesis that genetic background plays a primary role in modulating the synthesis of polyphenols and antioxidant compounds in bean seeds—a trend also reported in the studies conducted by Carbas et al. [41], Yang et al. [42], Yaneva et al. [43], García-Díaz et al. [44] or Kivu et al. [45]. Among the studied genotypes, Cozia3 consistently displayed the highest antioxidant content in seeds, indicating a superior capacity to synthesise or accumulate these compounds under favourable nutritional conditions. The individual effects of irrigation and fertilization did not lead to substantial changes in TPC levels in runner bean seeds, but their interaction with genotype had a pronounced impact on polyphenol accumulation. Antioxidant compound accumulation, as determined by the DPPH assay, was primarily influenced by fertilisation strategy and genotype, rather than

by irrigation alone. Chemical fertilisation resulted in a marked increase in antioxidant levels across treatments, suggesting a stimulatory effect on secondary metabolism.

Application of fertilizers and enhanced water availability appeared to promote the biosynthesis of secondary metabolites in seeds. The results associated with the interaction between irrigation and fertilisation showed that the IR2 × CH treatment produced the highest antioxidant levels, while the IR2 × OR treatment resulted in the lowest. This observation is consistent with the findings of Salas-Salazar et al. [84], who reported that variation in fertilisation regimes significantly alters the content of bioactive compounds in Pinto Centauro bean. Unlike our findings, Nina et al. [85] reported that water stress increased antioxidant accumulation in *Phaseolus vulgaris* L., highlighting the complex and context-dependent role of irrigation in modulating antioxidant metabolism. Taken together, these observations reinforce the view that both nutrient availability and water regime can modulate antioxidant profiles in a genotype-dependent manner.

4.5. Multivariate Relationships Among Traits

The traits associated with photosynthetic efficiency, seed productivity, and antioxidant capacity were the main contributors to overall variability, as PCA revealed, reflecting the combined influence of genotype, irrigation regime, and fertilisation type. These traits proved to be highly responsive to both environmental and genetic factors, highlighting their potential as reliable indicators of physiological performance and adaptability. Furthermore, Pearson correlation analysis confirmed these associations and showed that assimilation rate, CCI, seed weight percentage, grain yield, and seeds per pod had low to moderate positive correlations. This suggests that these factors are interconnected and influence overall productivity. According to Smith et al. [86] higher photosynthetic rates and greater chlorophyll content enable plants to capture more light and carbon dioxide for growth, directly increasing biomass and yield. Conversely, a strong negative correlation was found between the percentages of pericarp and seed weight, highlighting their complementary roles in pod structure. Photosynthetic traits (assimilation rate and CCI) were negatively correlated with antioxidant activity (DPPH and ABTS), suggesting a trade-off between growth efficiency and antioxidant accumulation. Additionally, yield-related traits showed weak to moderate negative associations with antioxidant capacity, indicating that higher productivity may come at the detriment of biochemical quality. In general, antioxidant compounds are synthesized in larger quantities as plant response to stress, helping to neutralize the effects of reactive oxygen species (ROS) that can negatively influence photosynthesis processes [87,88]. This explains the observed negative relationship between antioxidant levels and certain physiological parameters.

In addition, the PCA and Pearson correlation analyses conducted on data subsets organized by cultivar, irrigation regime, and fertilization type revealed notable differences in traits behaviour and variability (Figures S2–S4). Pearson's correlation analysis revealed genotype-specific relationships between physiological efficiency, yield, and antioxidant characteristics. For Cozia1, photosynthetic characteristics were found to be significantly correlated but negatively associated with grain morphology. In contrast, for Cozia2, there was a positive correlation between the assimilation rate and pod and seed characteristics, indicating that the absorbed nutrients are allocated both to support physiological processes and for breeding. Cozia3 showed moderate positive associations with yield components. In terms of antioxidant traits, Cozia1 and Cozia3 showed strong negative correlations between ABTS and assimilation rate and yield, while Cozia2 maintained weaker but more balanced relationships (Figure S2).

Analysis of data related to the irrigation regime revealed that, under IR1 conditions (lower irrigation quantity), the relationships between physiological traits and morpho-

agronomic characteristics ranged from weak to strong positive correlations. This suggests a substantial and beneficial interaction between functional traits and yield-related parameters. In contrast, under IR2 (higher irrigation level), between traits the relationships tended to be weakly positive or even negative, indicating a disruption in the coordination between physiological processes and agronomic performance, which is potentially due to waterlogging (Figure S3). As reported by Topali et al. [89] and Luo et al. [90], excessive irrigation can cause nutrient leaching and oxygen deficiency in the root zone, which may impair root function and plant development.

Concerning fertilization, this study's findings revealed that under chemical fertilization, the correlations among physiological, morphological, and biochemical variables were predominantly stronger and more consistent (Figure S4). This indicates an improved connection between plant functionality and productivity since chemical fertilizers, by directly supplying essential nutrients such as nitrogen, phosphorus, and potassium (NPK), provide plants with the elements necessary to simultaneously support various functions, inducing more robust root systems, greater biomass, and improved photosynthetic activity [91,92]. By contrast, the organic regime exhibited more balanced and selective correlations, particularly highlighting strengthened associations among seed traits, pointing to a more efficient internal allocation of resources under natural nutrient sources [36,37]. Meanwhile, the unfertilized condition was characterized by weak or even negative correlations, especially between physiological traits (e.g., assimilation rate) and biochemical traits (e.g., TPC, DPPH), indicating potential functional disruptions caused by nutrient limitation.

5. Conclusions

The findings of this study demonstrate that cultivar, irrigation regime, and fertilisation strategy significantly influence the physiological, morphological, and biochemical traits of runner bean, both individually and through interactive effects. Among these, genotype exerted the predominant influence under temperate conditions specific to the north-east region of Romania.

Cozia3 combined with chemical fertilisation proved to be the best option for achieving high yields under reduced water availability ($2000 \text{ m}^3 \cdot \text{ha}^{-1}$). In contrast, Cozia2 responded best to the combination of chemical fertilization and the highest irrigation level ($2500 \text{ m}^3 \cdot \text{ha}^{-1}$). For organic farming systems, Cozia3 was identified as the most suitable cultivar, maintaining both yield stability and quality traits. Additionally, Cozia2 showed the highest sensitivity to management practices, with pronounced variation in pod number, thousand grain weight, and seed traits across treatments. Furthermore, the results of this study showed that Cozia1 exhibited greater physiological stability, with photosynthetic parameters being less affected by irrigation and fertilization regimes compared to Cozia2 and Cozia3. Among the three cultivars, Cozia3 distinguished itself by accumulating the highest levels of antioxidant compounds, which reached maximum values under organic fertilisation combined with a reduced irrigation regime ($2000 \text{ m}^3 \cdot \text{ha}^{-1}$).

Overall, these findings provide valuable insights into the adaptability and performance of runner bean cultivars in temperate climates, emphasizing the importance of optimizing input combinations based on genotype-specific responses. However, further studies are needed to confirm these results across different environments and growing seasons. Future research should also consider the formal registration of these cultivars as official varieties. Moreover, given the comparable performance of organic and chemical fertilisation, investigating integrated nutrient management strategies, including the use of organic fertilisers combined with microbial biofertilisers, could support the development of more sustainable and resilient cultivation systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae11091135/s1>, Figure S1: Schematic representation of the experimental design; Figure S2: PCA score plots and Pearson correlation heatmaps showing the variation in physiological, biometric, and biochemical traits of runner bean under the influence of genotype; Figure S3: PCA score plots and Pearson correlation heatmaps showing the variation in physiological, biometric, and biochemical traits of runner bean under the influence of irrigation norm; Figure S4: PCA score plots and Pearson correlation heatmaps showing the variation in physiological, biometric, and biochemical traits of runner bean under the influence fertilization regime; Table S1: Eigenvalues of the correlation matrix showing the affinities of the physiological, biometric, and biochemical traits of runner bean to PCs; Table S2. Results of a three-way ANOVA test demonstrating the interaction among the experimental factors.

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