EVALUATING PHOTOSYNTHETIC ACTIVITY AND CHLOROPHYLL FLUORESCENCE IN MIRVAL F1 AND BLACK PEARL F1 EGGPLANT HYBRIDS CULTIVATED UNDER SIMILAR AGRONOMIC CONDITIONS

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RESEARCH ARTICLE

Abstract
Eggplant productivity depends strongly on how efficiently plants carry out photosynthesis and on the overall stability of their photosynthetic machinery. In this study, we compared two widely cultivated hybrids, Mirval F1 and Black Pearl F1, across three growing seasons (2019–2021) and under contrasting fertilization regimes: an unfertilized control, an organic input, and a synthetic chemical treatment. Using a portable gas-exchange system, we monitored core physiological parameters such as net CO_2 assimilation (A), transpiration, stomatal conductance, leaf temperature, internal CO_2, and incident light, all measured in steady mid-morning conditions. Chlorophyll fluorescence (Fv/Fm) was also recorded to check whether plants experienced any chronic photoinhibition. Across the three years, Mirval F1 maintained notably stable photosynthetic activity. Its CO_2 assimilation hovered around 6.0 µmol CO_2 $m^{-2}s^{-1}$ in the control plots and decreased only slightly under organic fertilization. Unexpectedly, chemical fertilization depressed assimilation to roughly 3.4, a response accompanied by warmer leaves and higher internal CO_2, signals that carbon processing was not keeping pace with nutrient availability. Black Pearl F1 behaved almost the opposite: photosynthesis was lowest without fertilization but improved gradually with additional nutrients, reaching nearly 4.7 µmol CO_2 $m^{-2}s^{-1}$ under chemical inputs. In parallel, stomatal conductance and transpiration also increased, implying a stronger reliance on external fertilization. Importantly, Fv/Fm values stayed high (≈0.83) across all treatments and years, meaning the photosystems themselves were not damaged. Overall, Mirval F1 appears physiologically resilient under low-input systems, while Black Pearl F1 performs best when nutrients are abundant, a distinction that can guide hybrid-specific, sustainable fertilization strategies.

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INTRODUCTION

Photosynthesis remains the core driver of vegetative growth, and in eggplant (Solanum melongena L.) its productivity tends to rise in parallel with physiological markers such as chlorophyll concentration and assimilation rate (Ciubotorita et al., 2022). Measurements of chlorophyll fluorescence add a second, quite necessary layer of interpretation to gas-exchange data; the well-established optimum of Fv/Fm around 0.83 in stress-free leaves (Murchie & Lawson, 2013) is often treated as a baseline, and even small drops below it usually indicate that the photosynthetic apparatus is already experiencing some degree of strain. Used together, these approaches give a rather complete image of a plant's photosynthetic stability.

Eggplant is cultivated under highly diverse fertilization practices, and nutrient management shapes not only yield but also the physiological "well-being" of the crop (Caruso et al., 2017; Islam et al., 2024; Basay et al., 2024). Chemical fertilizers deliver nutrients quickly and may stimulate growth, yet overuse sometimes triggers counterproductive responses, such as minor salt stress or excessively lush canopies that aren't very efficient (Farhan et al., 2024; Nadarajan et Sukumaran, 2021). Organic inputs, by contrast, release nutrients more gradually and tend to support a steadier photosynthetic rhythm while improving soil structure. Several studies even show that replacing part of the synthetic fertilizer with organic sources can enhance photosynthesis and resource-use efficiency (Zhang et al., 2023; Han et al., 2025; Chen et al., 2024; Mawlood et al., 2025). Still, the degree to which such practices sustain photosynthesis varies by genotype, since hybrids respond differently, sometimes unpredictably, to nutrient supply (Koutouleas et al., 2025).

Variation among eggplant genotypes in their photosynthetic behavior and fertilization response has long been noted, although it is sometimes understated in practice. Contemporary F1 hybrids often diverge quite sharply: certain lines maintain a naturally steady vigor, while others react more visibly and at times excessively, to nutrient supply (Lausin, 2025). Growers commonly remark that Mirval F1 performs reliably under a wide range of conditions, whereas Black Pearl F1 seems far more "hungry," showing stronger gains when nutrients are abundant but also occasional setbacks if fertilization is not well–balanced (Gerakali et al., 2025). These contrasts make it rather clear that uniform fertilization programs rarely fit all cultivars equally well.

In this study wore assessed the two hybrids under comparable field conditions but exposed to three fertilization regimes: an unfertilized control, an organic treatment, and a chemical one. Across three seasons gas-exchange traits were monitored together with chlorophyll fluorescence to track year-to-year stability and any stress-related deviations. The working assumption was that Mirval F1 would retain relatively consistent photosynthetic rates even under organic inputs, while Black Pearl F1 would respond more strongly to fertilization, especially chemical sources, though possibly at the cost of greater transpiration. By examining multi-year patterns, the study aimed to clarify how each hybrid's physiology is shaped by organic versus inorganic nutrition and to outline more cultivar-sensitive fertilization strategies that support productivity without compromising longer-term sustainability.

MATERIAL AND METHOD

The study was carried out across three consecutive seasons, 2019 to 2021, using two commercial eggplant hybrids, Mirval F1 from and Black Pearl F1, grown together under the same field conditions. Seedlings were transplanted each late spring into open plots at a research farm in northeastern Romania, where the climate is temperate continental and the soil is a moderately fertile chernozem that drains fairly well. A split-plot arrangement was used with the hybrid treated as one factor and the fertilization regime as the second factor, although in practice the interactions were sometimes less clean than we expected.

Three fertilization treatments were established. The control plots received no added fertilizers, only the native soil nutrients and identical basic care. The biological treatment relied on well-decomposed manure and plant-based biostimulants, intended to support natural nutrient release and stimulate soil life. In the chemical treatment, plants were given mineral NPK fertilizers at the standard rates for eggplant, applied in several portions during the season. All treatments were repeated consistently in every year. Plots were set in randomized blocks with three replications for each hybrid and fertilization combination. Each plot contained roughly 15 to 20 plants, which was enough for the physiological measurements we planned. Routine field practices such as irrigation, weeding and pest control were kept identical so that fertilization remained the only real source of variation.

Physiological Measurements

Gas exchange and fluorescence measurements were taken from fully expanded leaves situated around the middle of the canopy during the fruiting period, when photosynthesis is usually at its most active. To reduce the usual fluctuations during the day, readings were collected on clear mornings between roughly 9:30 and 10:30 a.m., although in a few cases we had slight delays that did not seem to affect patterns. An LCpro plus system from ADC BioScientific was used to quantify net CO_2 assimilation, transpiration, stomatal conductance and the internal CO_2 concentration. The instrument operated under ambient air, with CO_2 kept close to atmospheric values near 400 μmol mol^{-1}, and sensor flow was adjusted according to the manual, although not always perfectly. Leaf temperature and incident photon flux were recorded simultaneously with the chamber's built in sensors. Leaves were allowed to stabilize inside the chamber for about two minutes before any values were saved. For each treatment three to five leaves was measured in every plot and the mean values were used for later statistical evaluation.

Chlorophyll fluorescence was obtained with a portable modulated fluorometer from Hansatech Instruments to evaluate the efficiency of photosystem II. Several leaves per treatment were dark adapted for approximately half an hour and Fv/Fm was determined either before sunrise or very early in the morning. The usual measuring beam was followed by a saturating pulse in order to derive F_0 and Fm. Light adapted parameters were also taken from sunlit leaves so that fluorescence information would correspond with the gas exchange data and help verify that no chronic stress processes had been overlooked.

Data Analysis

For every treatment and year, the measurements were summarized as mean values with their standard errors, although in a few cases the variation looked a bit uneven. To check how stable the data were across seasons, we compared the values from 2019, 2020 and 2021 within each hybrid. A combined ANOVA was then applied to evaluate the effects of fertilization, year and the interaction between them on the main physiological traits such as assimilation, transpiration, stomatal conductance, internal CO_2, leaf temperature and Fv over Fm. Before running the tests, the data were inspected for normal distribution and equal variances and, when needed, log or arc sine transformations were applied so that the assumptions of ANOVA were at least reasonably met. Because the year factor turned out to have only small influence, the three seasons were also pooled to compare fertilization treatments using either Duncan or Tukey tests at the 5 percent significance threshold. Ratios such as intrinsic water use efficiency, which was calculated as assimilation divided by transpiration, and simple indicators of carboxylation efficiency were examined descriptively to give a broader physiological context. All analyses were carried out with Statistica version 13. Throughout the results and discussion sections, any treatment differences mentioned are significant at the five percent level unless otherwise stated.

RESULTS AND DISCUSSIONS

Across the three seasons, both hybrids showed a fairly stable pattern of photosynthetic activity, with only small year to year shifts that were probably linked to minor changes in weather. Such stability suggests that the measurement approach was reliable and that the physiological traits of these cultivars are not easily disturbed, although some variation surely occurs that cannot always be captured. In this research are presented the responses of Mirval F1 and Black Pearl F1 under the different fertilization treatments and then compare the two hybrids to underline the main contrasts among regimes.

1. Photosynthesis Analysis in Mirval F1 Hybrid

1.1 Photosynthetic Performance Under Control Conditions (2019–2021)

Under the unfertilized control conditions, Mirval F1 showed a very steady photosynthetic activity throughout the three seasons. The assimilation rate remained close to 6 μmol CO_2 m^{-2} s^{-1} in every year, and none of the small numerical differences reached statistical meaning. This near constancy suggests that the hybrid's photosynthetic system functioned efficiently and was hardly influenced by the slight shifts in sampling dates or by the modest weather differences among seasons. Even when measurements were taken a bit earlier in one year or slightly later in another, the values changed so little that it is difficult to attribute any biological relevance to them. Such interannual stability points to a strong inherent robustness, which in practical terms means that growers can expect Mirval F1 to perform quite predictably under low input conditions, even when field operations do not occur with perfect timing

The accompanying physiological traits confirmed the same pattern of steadiness in Mirval F1 under control conditions (Sharma et al., 2025; Ashraf et al., 2025). Transpiration remained close to 3.2 mmol H_2O m^{-2} s^{-1} in all seasons, and stomatal conductance stayed around 0.31 to 0.32 mol H_2O m^{-2} s^{-1}, suggesting that stomatal opening was regulated in almost the same manner every year. The alignment among assimilation, transpiration and conductance implies that the hybrid maintained a rather stable balance between carbon gain and water loss, a behavior often seen in genotypes with good homeostatic control, even though small environmental shifts did occur (Flcioni et al., 2025).

Other variables were similarly constant. Internal CO_2 concentration varied only slightly around 341 to 343 μmol mol^{-1}, which indicates that diffusion into the leaf and biochemical fixation stayed well matched. Leaf temperature during measurements was near 30 °C, a level generally favorable for eggplant photosynthesis, so no year appeared to introduce thermal stress. Light availability at the leaf surface also changed very little, remaining around 265 μmol m^{-2} s^{-1}.

Taken together, these multi year observations show that Mirval F1 is physiologically resilient under unfertilized conditions. The hybrid seems able to buffer modest climatic fluctuations and small timing irregularities in field measurements. For growers, such stability means that Mirval often performs predictably in environments where conditions vary from one season to another, which reduces the likelihood of unexpected declines in photosynthetic functioning or yield.

Table 1.

Photosynthetic performance of Mirval F1 under control conditions (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	6.05 ± 0.25	6.01 ± 0.22	6.07 ± 0.20
Transpiration (E, mmol m^{-2} s^{-1})	3.18 ± 0.10	3.20 ± 0.11	3.21 ± 0.09
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.31 ± 0.01	0.32 ± 0.01	0.32 ± 0.01
Internal CO_2 concentration (Ci, μmol mol^{-1})	342 ± 6	343 ± 5	341 ± 7
Leaf temperature (Tl, °C)	29.8 ± 0.3	29.9 ± 0.2	30.0 ± 0.3
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	265 ± 8	267 ± 7	264 ± 9

1.2 Photosynthetic performance under biological (Organic) fertilization (2019–2021)

The use of biological fertilization in Mirval F1 offered the opportunity to see whether organic nutrient sources could preserve the high and steady photosynthetic activity observed in the control plants. Across the three seasons, the hybrid responded in a remarkably consistent way, with only small year to year shifts that largely resembled the stability already noted in the unfertilized treatment.

Assimilation rates under organic inputs ranged between about 5.6 and 5.8 μmol CO_2 m^{-2} s^{-1}, values only slightly lower than the control and without any significant seasonal differences. This suggests that the hybrid kept an efficient carbon fixation capacity even when nutrients came from slow releasing organic materials. The stability of these values indicates that the organic regime did not create physiological stress or any form of cumulative decline, something that sometimes happens in field studies even if it is not intended it (Yang et al., 2025).

Although the mean assimilation was a little below the control level, the steadiness from year to year points to a metabolic system that functions reliably under moderate organic nutrition. Such behavior fits with what is known about organic fertilizers, which tend to improve soil conditions and provide nutrients gradually.

Table 2.

Photosynthetic performance of Mirval F1 under biological fertilization (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	5.82 ± 0.35	5.61 ± 0.30	5.74 ± 0.28
Transpiration (E, mmol m^{-2} s^{-1})	3.20 ± 0.11	3.25 ± 0.12	3.28 ± 0.10
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.27 ± 0.01	0.26 ± 0.01	0.27 ± 0.01
Internal CO_2 concentration (Ci, μmol mol^{-1})	345 ± 7	339 ± 6	342 ± 8
Leaf temperature (Tl, °C)	30.7 ± 0.3	30.6 ± 0.3	30.8 ± 0.2
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	240 ± 9	231 ± 8	238 ± 7

Under organic fertilization, Mirval F1 showed almost the same steadiness in leaf physiology as in the control treatment. Transpiration stayed close to 3.2 mmol m^2 s^{-1} in all three seasons, which indicates that the organic inputs did not disturb the plant's water balance. Stomatal conductance was slightly lower, around 0.26 to 0.27 mol m^2 s^{-1} compared with the control, suggesting a somewhat more cautious stomatal behavior, although this difference remained very consistent from year to year. Even with this small reduction, assimilation stayed nearly unchanged and internal CO_2 concentration varied only a few units around 340 μmol mol^{-1}, which shows that carbon fixation kept pace with CO_2 supply.

Leaf temperature under organic management was close to 31 °C, only a little above the control, and well within the safe thermal range for eggplant. Light reaching the measured leaves was somewhat lower than in the control plots, but the assimilation rate did not decline proportionally, which suggests that the plants used the available radiation efficiently. None of these parameters showed meaningful seasonal fluctuations, which supports the view that the organic nutrient regime did not introduce physiological stress.

Taken together, Mirval F1 maintained a stable photosynthetic functioning under organic inputs, with assimilation only slightly below the unfertilized control and with water use, internal CO_2 and leaf temperature remaining almost identical. These results indicate that the hybrid performs reliably when supplied with organic amendments and that the modest changes observed are unlikely to have major agronomic consequences.

1.3 Photosynthetic performance under chemical fertilization (2019–2021)

Mirval F1 was also assessed under conventional chemical fertilization to see how its photosynthetic system reacts when nutrients are supplied in readily available mineral form. Across the three seasons, the hybrid again showed internal consistency, although the overall magnitude of its response differed sharply from that in the control and organic treatments. Net assimilation remained close to 3.4 μmol CO_2 m^2 s^{-1} in all years, with almost no seasonal fluctuation, which suggests that the hybrid maintained a stable physiological pattern even under this fertilization regime (Abbas et al., 2025).

However, the level of assimilation was much lower than in the unfertilized and organic conditions. Chemical inputs produced only about half of the control rate, indicating that Mirval's photosynthetic apparatus did not benefit from the extra mineral nutrients. The reduced assimilation may imply that the plants were already functioning near their physiological capacity without added fertilizer, and the higher nutrient load perhaps altered internal balances in a way that did not support carbon fixation. For instance, rapid vegetative growth or mild salt related stress cannot be ruled out as factors that might have limited the photosynthetic response.

The persistence of this reduced assimilation across the three years indicates that the effect was consistent rather than incidental. This pattern suggests that Mirval F1 does not rely on high mineral nutrient availability for optimal photosynthetic activity and may even perform less efficiently under such conditions.

Table 3.

Photosynthetic performance of Mirval F1 under chemical fertilization (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	3.41 ± 0.22	3.47 ± 0.20	3.44 ± 0.21
Transpiration (E, mmol m^{-2} s^{-1})	3.51 ± 0.09	3.52 ± 0.08	3.49 ± 0.10
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.23 ± 0.01	0.23 ± 0.01	0.22 ± 0.01
Internal CO_2 concentration (Ci, μmol mol^{-1})	353 ± 7	357 ± 6	355 ± 8
Leaf temperature (Tl, °C)	32.1 ± 0.2	32.2 ± 0.3	32.3 ± 0.2
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	240 ± 11	243 ± 9	241 ± 10

Under chemical fertilization, Mirval F1 showed a small but consistent rise in transpiration to about 3.5 mmol m^2 s^{-1}, exceeding both the control and organic treatments. This higher water loss likely reflects slightly larger foliage or more frequent stomatal opening. However, this change was not accompanied by any increase in assimilation, which remained low. As a consequence, water use efficiency declined and the plants behaved as more water demanding without gaining additional carbon, a response often seen when mineral nutrients promote excessive vegetative growth without improving photosynthetic efficiency.

Stomatal conductance decreased slightly to around 0.22 to 0.23 mol m^2 s^{-1}, below control values, indicating that the limitation on assimilation was mainly biochemical rather than stomatal. Internal CO_2 concentration increased to about 353 to 357 μmol mol^{-1}, suggesting that CO_2 entered the leaf but was used less effectively. Leaf temperature also rose to nearly 32 °C, still within a safe range but sufficient to enhance photorespiration and reduce net carbon gain. The combined increase in Ci and temperature points to a mild metabolic imbalance affecting the Calvin cycle.

Light levels during chemical treatment were close to those in the organic plots and only slightly lower than in the control, around 240 μmol m^2 s^{-1}, values that normally support high assimilation in Mirval. Yet assimilation remained at about half of the control rate, indicating a clear decline in light use efficiency, likely linked to enzymatic or source to sink constraints.

Chemical fertilization induced a stable but clearly reduced photosynthetic performance in Mirval F1. Gas exchange remained regulated, yet assimilation stayed low while water loss increased modestly. These results indicate that Mirval responds better to moderate or organic nutrition, where its metabolism remains more balanced and efficient, rather than to intensive mineral input.

1.4 Comparative analysis of Mirval F1 photosynthesis across treatments (2019–2021)

Comparing Mirval F1 across the three fertilization regimes clarifies how this hybrid adjusts its photosynthetic behavior in relation to nutrient supply. Although stability from year to year remained high, the absolute values of the physiological traits differed strongly among treatments.

Assimilation was highest in the control at nearly 6 μmol CO_2 m^2 s^{-1}, only slightly lower under organic nutrition at about 5.7, but dropped sharply to around 3.4 under chemical fertilization. This shows that Mirval performed best without added nutrients, while organic inputs caused only minor limitation. In contrast, the chemical regime clearly suppressed assimilation, suggesting that excess mineral supply did not support, and may even have restricted, photosynthetic activity.

Transpiration remained near 3.2 mmol m^2 s^{-1} in the control and organic treatments but increased to roughly 3.5 under chemical fertilization. Since assimilation did not rise accordingly, intrinsic water use efficiency declined in chemically treated plants. Stomatal conductance followed the same order, with the highest values in the control and the lowest under chemical input, indicating reduced demand for CO_2 when assimilation was low.

Internal CO_2 concentrations were similar in the control and organic treatments, near 342 μmol mol^{-1}, showing a balanced CO_2 supply and fixation. Under chemical fertilization, Ci increased to about 355, which points to less effective carbon fixation despite adequate CO_2 entry. Leaf temperatures were lowest in the control and highest under chemical input, close to 32 °C. While still acceptable, this rise may favor photorespiration under hot weather. Light levels were highest in the control and slightly lower in organic and chemical plots. Despite receiving less light, organic plants maintained high assimilation, whereas chemically fertilized plants showed clearly reduced light use efficiency.

Table 4.

Comparative photosynthetic parameters of eggplant (2019–2021)

Physiological parameter	Control	Biological	Chemical	Comparative observations
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	~6.0	~5.7	~3.4	Highest in control, lowest in chemical
Transpiration (E mmol m^{-2} s^{-1})	~3.2	~3.25	~3.5	Slight increase under chemical
Stomatal conductance (gs, mol m^{-2} s^{-1}	~0.32	~0.27	~0.23	Maximum in control
Internal CO_2 concentration (Ci, μmol mol^{-1})	~342	~342	~355	Higher under chemical
Leaf temperature (Tl, °C)	~29.9	~30.7	~32.2	Increases with chemical input
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	~265	~236	~241	Most efficient in control

Taken together, the comparisons show that Mirval F1 reached its highest photosynthetic activity in the unfertilized control plots. Although it might seem intuitive that added nutrients would stimulate higher assimilation, the data suggest that the basic soil fertility and the hybrid's own genetic traits were already sufficient for near maximal performance. The organic regime followed closely behind the control, with only small reductions in the main gas exchange parameters and with a similarly stable behavior across years. Chemical fertilization, while not destabilizing the physiology, led to a noticeably lower operating level, as if the plants maintained a safe but less efficient mode of functioning.

These patterns are consistent with results reported by Acatrinei and colleagues (Acatrinei et al., 2019). Those experiments also noted higher assimilation and wider stomatal conductance in unfertilized plants, with marked declines under mineral nutrition. The agreement across datasets strengthens the view that Mirval does not translate high nutrient supply into higher leaf photosynthesis and in some cases may even be hindered by it.

From an agronomic point of view, this suggests that Mirval F1 does not require heavy fertilization to achieve strong physiological or yield performance. Standard nutrient supply or an organic program is likely adequate, and

excessive mineral inputs could be counterproductive. The high stability of its photosynthetic traits also implies that Mirval is well suited for environments where weather and management timing vary from year to year.
Fertilization mainly shifts the level of photosynthetic activity rather than its consistency. Mirval performs best under low or organic inputs and remains reliable even when conditions fluctuate. Yield trials that report comparable or higher productivity under organic systems further support these physiological observations, showing that more fertilizer does not necessarily improve this hybrid's performance.

2. Photosynthesis analysis in Black Pearl F1 Hybrid

Black Pearl F1 was the second hybrid evaluated, and its behavior contrasted sharply with that of Mirval. Growers often remark that Black Pearl responds strongly to high nutrient supply (Sidhu, 2004), and the present data support this observation. Under unfertilized conditions the hybrid showed relatively low assimilation, yet its photosynthetic activity rose noticeably when organic or chemical nutrients were provided. As with Mirval, the year to year variation within each treatment remained small, but the overall direction of change differed. Instead of showing reduced performance with added nutrients, Black Pearl improved under both fertilization regimes.

2.1 Photosynthetic performance under control conditions (2019–2021)

Under unfertilized control conditions, Black Pearl F1 displayed a moderate level of photosynthetic activity that remained quite steady across the three seasons. Measurements were taken at similar morning hours on mild days, which helped ensure that the values were comparable. The assimilation rate averaged about 3.3 μmol CO_2 m^2 s^{-1} each year, and no meaningful differences appeared among the seasons, showing that the hybrid maintains stable functioning even when nutrient supply is minimal.
Although this stability mirrors the pattern seen in Mirval, the absolute level of assimilation was much lower. Black Pearl's photosynthetic capacity without added nutrients was roughly half of Mirval's, which points to intrinsic physiological differences, possibly related to leaf structure or enzyme activity. Even so, the hybrid showed reliable performance at this lower baseline. For growers, this means that Black Pearl can sustain predictable photosynthesis under low input conditions, although its potential for carbon assimilation remains limited unless additional nutrients are supplied.

Table 5.
Photosynthetic performance of Black Pearl F1 under control conditions (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	3.32 ± 0.23	3.35 ± 0.21	3.37 ± 0.22
Transpiration (E, mmol m^{-2} s^{-1})	3.38 ± 0.09	3.40 ± 0.08	3.36 ± 0.08
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.21 ± 0.01	0.22 ± 0.01	0.21 ± 0.01
Internal CO_2 concentration (Ci, μmol mol^{-1})	349 ± 6	352 ± 7	351 ± 8
Leaf temperature (Tl, °C)	32.2 ± 0.2	32.3 ± 0.3	32.1 ± 0.2
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	232 ± 9	236 ± 11	234 ± 10

Under unfertilized conditions, Black Pearl F1 maintained a stable but modest level of gas exchange over the three years. Transpiration remained near 3.4 mmol m^2 s^{-1} and stomatal conductance around 0.21 mol m^2 s^{-1}, showing almost no interannual variation. This moderate stomatal opening resulted in a low assimilation to transpiration ratio near 1.0, indicating a lower intrinsic water use efficiency than in Mirval. Although water loss was comparable, carbon fixation was much lower, which reflects a conservative baseline physiology rather than any visible stress.

Internal CO_2 concentration stayed close to 350 μmol mol^{-1}, confirming that CO_2 supply was sufficient but biochemical capacity for fixation was limited under poor nutrition. Leaf temperature averaged slightly above 32 °C and remained consistent across years, which indicates stable microclimatic conditions and no thermal impairment of photosynthesis. Light levels were moderate and similar each season, around 234 μmol m^2 s^{-1}, suggesting that the hybrid was operating below light saturation and likely constrained more by nutrients than by radiation.

Overall, Black Pearl F1 showed a steady but low photosynthetic profile under control conditions. The hybrid remained physiologically balanced, yet its carbon gain was clearly limited without fertilization, providing a reliable baseline for assessing nutrient responses later on.

2.2 Photosynthetic performance under biological (Organic) fertilization (2019–2021)

Organic fertilization produced a clear and positive shift in the photosynthetic behavior of Black Pearl F1, raising assimilation well above control values while keeping the year to year variation minimal. This response illustrates how strongly the hybrid can benefit from a steady supply of nutrients released from organic materials (Stoleru et al., 2016).

With organic inputs, assimilation increased to around 4.0 µmol CO_2 m^2 s^{-1} in every season, a rise of roughly 20 percent compared with the unfertilized plants. The near identical values across years show that the organic treatment delivered nutrients in a reliable way and that the hybrid responded with a consistently higher photosynthetic activity. Although this improved rate remained below the maximum values observed in Mirval, it still represents a meaningful enhancement of Black Pearl's own capacity.

The predictability of the response suggests that organic fertilization can support a sustained upgrade of the photosynthetic machinery, likely by improving nitrogen availability and related biochemical functions, indicating that organic practices can provide both a noticeable increase in performance and a stable physiological trajectory for Black Pearl across different seasons.

Table 6.

Photosynthetic performance of Black Pearl F1 under biological (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, µmol CO_2 m^{-2} s^{-1})	3.95 ± 0.11	3.99 ± 0.12	3.97 ± 0.13
Transpiration (E, mmol m^{-2} s^{-1})	4.01 ± 0.10	4.04 ± 0.11	4.00 ± 0.09
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.26 ± 0.01	0.27 ± 0.01	0.26 ± 0.01
Internal CO_2 concentration (Ci, µmol mol^{-1})	342 ± 7	345 ± 8	344 ± 7
Leaf temperature (Tl, °C)	33.1 ± 0.3	33.2 ± 0.3	33.3 ± 0.3
Photosynthetic photon flux (Qleaf, µmol m^{-2} s^{-1})	205 ± 11	210 ± 10	208 ± 12

Under organic fertilization, Black Pearl F1 showed a clear rise in transpiration to about 4.0 mmol m^2 s^{-1}, compared with roughly 3.4 in the control. This increase occurred together with higher assimilation and stomatal conductance, which reached about 0.26 mol m^2 s^{-1}. The parallel rise of these parameters indicates that water use efficiency remained generally stable, with the plant gaining more CO_2 without a disproportionate increase in water loss.

Internal CO_2 concentration remained near 343 µmol mol^{-1} and was slightly lower than in unfertilized plants, suggesting that the extra CO_2 was being fixed more effectively. This points to an improvement in carboxylation capacity under organic nutrition, most likely due to better enzyme activity. Leaf temperature stayed close to 33 °C and no signs of thermal stress or photochemical damage were observed, as Fv over Fm values remained normal.

Light intensity during organic treatment was lower than in the control, near 208 µmol m^2 s^{-1}, yet assimilation was higher. This shows that the enhanced photosynthesis was driven mainly by improved nutrition rather than by light availability. In overall, Black Pearl exhibited a stable and efficient physiological adjustment to organic inputs, with assimilation increasing by about twenty percent.

2.3 Photosynthetic performance under chemical fertilization (2019–2021)

When Black Pearl F1 received chemical fertilization, its photosynthetic activity increased markedly, showing an even stronger stimulation than under organic inputs. Across all three seasons, the hybrid made full use of the readily available mineral nutrients and reached its highest assimilation values, together with proportional rises in the other gas exchange traits. The year to year pattern was very consistent, which indicates that this response was not accidental but rather a stable feature of the genotype under these conditions.

Assimilation averaged close to 4.7 µmol CO_2 m^2 s^{-1} in each of the three years, which represents an increase of roughly forty percent compared with the unfertilized control and about one fifth more than in the organic treatment. The near identical values across seasons show that chemical fertilization pushed Black Pearl to a higher physiological level and kept it there. For morning measurements taken at moderate light, these rates are fairly high and point to a vigorous photosynthetic metabolism.
Unlike Mirval, which declined when supplied with mineral nutrients, Black Pearl showed a

strong positive response, confirming that it is a genotype that depends heavily on nutrient availability to express its photosynthetic potential.

Table 7.

Photosynthetic performance of Black Pearl F1 under chemical (2019–2021)

Physiological parameter	2019 (mean ± SE)	2020 (mean ± SE)	2021 (mean ± SE)
Net assimilation (A, μmol CO_2 m^{-2} s^{-1})	4.65 ± 0.15	4.71 ± 0.14	4.73 ± 0.16
Transpiration (E, mmol m^{-2} s^{-1})	4.70 ± 0.12	4.74 ± 0.11	4.75 ± 0.13
Stomatal conductance (gs, mol m^{-2} s^{-1})	0.29 ± 0.01	0.30 ± 0.01	0.30 ± 0.01
Internal CO_2 concentration (Ci, μmol mol^{-1})	345 ± 8	348 ± 7	346 ± 9
Leaf temperature (Tl, °C)	33.3 ± 0.3	33.4 ± 0.3	33.5 ± 0.3
Photosynthetic photon flux (Qleaf, μmol m^{-2} s^{-1})	285 ± 12	295 ± 13	290 ± 11

Under chemical fertilization, Black Pearl F1 displayed a marked rise in transpiration, reaching about 4.7 mmol m^2 s^{-1} in each season, roughly forty percent above the control. This increase occurred alongside higher assimilation, so water use efficiency stayed broadly similar to the unfertilized plants, although slightly below the values recorded under organic inputs. The stronger water loss likely reflected a larger canopy and more active stomata, a common outcome when nutrient supply is high. Because irrigation was maintained, no dought effects appeared, but such plants would need good water provision in practical production.

Stomatal conductance also rose, reaching around 0.30 mol m^2 s^{-1}, which was higher than in the control or organic treatments. This matched the increased assimilation and transpiration, indicating that stomata were opening more freely and supplying the leaf with the CO_2 needed to sustain the higher metabolic rate. This coordinated change contrasts with Mirval, where chemical fertilization did not yield similar gains.

Internal CO_2 concentration remained stable at around 345 to 348 μmol mol^{-1}, suggesting that the CO_2 entering the leaf was used efficiently rather than accumulating, balance that implies that the biochemical pathway of carbon fixation was well supported by the nutrient supply. Leaf temperature stayed near 33 to 33.5 °C, which is safe for eggplant, and the high transpiration probably prevented excessive warming.

Leaves in the chemical treatment received more light, roughly 285 to 295 μmol m^2 s^{-1}, either because of brighter measurement conditions or a more open canopy. The plants used this light effectively and reached their highest assimilation rates, and the consistency across years confirms that the response is reliable.

Black Pearl F1 showed a strong and repeatable enhancement of photosynthesis under chemical fertilization. All major gas exchange traits increased without any sign of physiological instability. This behavior differs sharply from Mirval and shows that Black Pearl is highly responsive to nutrient supply. For production, chemical fertilization can substantially raise its performance, although maintaining adequate water and combining mineral with organic sources may provide a more balanced and resilient management strategy.

2.4 Comparative analysis of Black Pearl F1 photosynthesis across treatments (2019–2021)

Across the three fertilization regimes, Black Pearl F1 displayed a very regular progression in its physiological response, one that contrasts with the pattern seen in Mirval. As nutrient availability increased from the control treatment to the organic and then the chemical regime, photosynthetic activity rose accordingly. This gain was accompanied by higher water use and slightly warmer leaves, which indicates a need for careful management when cultivation becomes more intensive.

Net CO_2 assimilation increased from about 3.4 μmol m^2 s^{-1} in unfertilized plants to around 4.0 under organic inputs and nearly 4.7 with chemical nutrition, values that suggest that Black Pearl has a considerable reserve of unused capacity when grown without added nutrients and that fertilization gradually brings it closer to its physiological potential. This pattern is opposite to Mirval, which reached its highest assimilation in the absence of fertilization, and it implies that Black Pearl is more compatible with high input systems.

Transpiration followed a similar rise, from roughly 3.3 mmol m^2 s^{-1} in the control to near 4.0 in organic plots and around 4.7 in chemically fertilized plants. The hybrid appears to respond to richer nutrition by widening stomata and possibly expanding leaf area. Such changes enhance carbon gain but also raise water needs, meaning that irrigation must be reliable if the hybrid is grown intensively or in warm climates.

Stomatal conductance increased from about 0.22 mol m^2 s^{-1} in the control to roughly 0.26 with organic inputs and around 0.30 under chemical fertilization. The higher conductance indicates that stomata opened more readily as nutrient supply improved, which corresponds well with the higher assimilation. The internal CO_2 concentration, however, remained relatively stable across treatments, suggesting that CO_2 entering the leaves was processed efficiently. This stable Ci response differs from Mirval, where chemical fertilization caused a noticeable rise.

Leaf temperatures were slightly higher in the fertilized plants, generally around 33 °C, but still within the tolerated range for eggplant. Even so, these values suggest that Black Pearl under strong fertilization might reach thermal limits more quickly in hot weather. Light intensity at the leaf surface also tended to be higher in chemically fertilized plants, and the hybrid appeared capable of using this additional light without signs of stress.

Taken together, Black Pearl F1 demonstrates a coordinated enhancement of gas exchange and light use when fertilized, maintaining balanced internal CO_2 and manageable leaf temperatures. These traits underline its suitability for nutrient rich cultivation systems where maximizing photosynthesis is a primary goal.

Table 8.

Comparative photosynthetic performance of Black Pearl F1 (2019–2021)

Physiological parameter	Control	Biological	Chemical	Observations
Net assimilation (A, µmol CO_2 m^{-2} s^{-1})	~3.4	~3.9–4.0	~4.7	Highest under chemical
Transpiration (E, mmol m^{-2} s^{-1})	~3.3	~3.8–4.0	~4.7	Maximum under chemical
Stomatal conductance (gs, mol m^{-2} s^{-1})	~0.22–0.23	~0.25–0.27	~0.29–0.31	Increases control → chemical
Internal CO_2 concentration (Ci, µmol mol^{-1})	~345–350	~340–345	~348–352	Slightly higher under chemical
Leaf temperature (Tl, °C)	~32.1–32.3	~33.0–33.5	~33.3–33.8	Higher with fertilization
Photosynthetic photon flux (Qleaf, µmol m^{-2} s^{-1})	~230–250	~200–230	~270–300	Highest under chemical

When the three fertilization regimes are compared side by side, Black Pearl F1 shows a pattern that is almost the mirror image of Mirval. Mirval performed best without added nutrients, while Black Pearl reached its lowest photosynthetic rates in the control and improved steadily with organic and then chemical fertilization. The chemical treatment produced the strongest response, indicating that this hybrid is adapted to high nutrient availability. Although this came with slightly greater water loss and warmer leaves, these effects were comparatively modest. Organic fertilization also enhanced Black Pearl's assimilation, though to a lesser degree, and with a somewhat better balance between carbon gain and water use.

The differences between organic and chemical inputs are noteworthy. Chemical fertilization increased net assimilation by about 0.7 µmol m^2 s^{-1}, but the same increase appeared in transpiration, suggesting that the benefit in carbon gain is partly offset by a higher water cost. Internal CO_2 levels were slightly lower under organic inputs, indicating that CO_2 was used a bit more efficiently. This pattern hints that organic fertilization may offer a more favorable compromise between high photosynthesis and water conservation, even if chemical nutrients still push assimilation to its upper range.

Given these results, a combined nutrient strategy may be ideal for Black Pearl. Integrating organic materials with a moderate fraction of chemical fertilizer, as seen in other crops, could help maintain high photosynthetic activity while improving water and nitrogen efficiency. Black Pearl's strong responsiveness means it can reward intensive management, but it also requires consistent water availability and may react more sharply to sudden stress events. Mirval, on the other hand, behaves in a more resilient and input-independent manner. It maintains high photosynthesis even with minimal fertilization and shows little improvement when more nutrients are supplied. These contrasting profiles suggest that each hybrid aligns with a different production system: Black Pearl suits high input systems aimed at maximal yields, while Mirval is better adapted to low input or resource limited environments.

Taken together, the data emphasize that fertilization strategies should be chosen with the hybrid's physiological tendencies in mind. Considering ratios such as assimilation over transpiration or yield per water use would help growers decide which hybrid and nutrient regime are most suitable for local conditions, particularly where water is constrained.

CONCLUSIONS

The three-year comparative experiment clearly demonstrates that fertilization strategy exerts a strong and differentiated influence on the photosynthetic behaviour of the two eggplant hybrids, Mirval F1 and Black Pearl F1, while also reinforcing the need for genotype-adapted nutrient management. Mirval F1 exhibited a remarkable degree of physiological stability and reached its highest photosynthetic activity under unfertilized conditions, with organic fertilization maintaining a comparably elevated level of assimilation. By contrast, chemical fertilization in this hybrid was associated with a visible decline in net CO_2 uptake, most probably linked to internal metabolic disturbances or limitations in gas diffusion, even though the interannual stability of its response remained largely unchanged. These patterns indicate that Mirval F1 is particularly well suited for low-input or organic production systems, where its photosynthetic machinery can operate close to optimum without the need of intensive mineral inputs. Its robust physiological configuration appears to provide a certain buffering capacity against moderate environmental variability, which may translate into stable yields even under fluctuating climatic conditions.

Black Pearl F1, in turn, displayed a markedly different physiological profile, behaving as a hybrid strongly responsive to nutrient availability. Under organic fertilization, Black Pearl recorded a clear increase in CO_2 assimilation and stomatal conductance, resulting in enhanced carbon gain while largely preserving water-use efficiency. When supplied with chemical fertilizers, this hybrid achieved the highest assimilation rates across all treatments, although this was accompanied by increased transpiration and a slight decline in water-use efficiency. Such a response suggests that Black Pearl F1 is able to support intensive growth and high productivity under well-fertilized conditions, but at the cost of higher water demand and a narrower safety margin against stress, especially under hot or dry weather. In these situations, careful irrigation scheduling and attention to canopy temperature becomes, more than optional, a technical necessity.

From a practical standpoint, these results support the adoption of differentiated fertilization strategies. Producers targeting sustainable systems with reduced chemical inputs may preferentially select Mirval F1, or apply organic fertilization to Black Pearl F1, thus taking advantage of their high photosynthetic stability and improved water-use efficiency under these regimes. Conversely, in high-input production systems oriented toward maximum yield, Black Pearl F1 combined with controlled chemical fertilization, possibly supplemented with organic amendments to protect soil structure, appears to be a more appropriate choice, given its pronounced photosynthetic response to elevated nutrient supply. For both hybrids, however, maintaining a functional balance between CO_2 assimilation and transpiration remains essential. Agronomic interventions that help stabilize this balance, such as partial substitution of mineral fertilizers with organic sources, optimized irrigation, and basic microclimate management, may en

Chlorophyll fluorescence analysis further showed Fv/Fm values close to 0.83 across all treatments, indicating that none of the fertilization regimes induced chronic photoinhibition in either hybrid. This finding is particularly relevant, as it confirms that the observed differences in gas-exchange performance were primarily rooted in regulatory and metabolic adjustments rather than in structural damage to photosystem II. Both Mirval F1 and Black Pearl F1 maintained high photochemical efficiency, implying that potential yield differences are mainly determined by how effectively each hybrid converts available resources, nutrients, water and light, into photosynthates, not by any fundamental impairment of the photosynthetic apparatus.

Overall, by integrating gas-exchange parameters with chlorophyll fluorescence measurements, the present study reveals that Mirval F1 and Black Pearl F1 exhibit contrasting yet consistent physiological strategies in response to fertilization. A clear understanding of these differences allows for more rational and evidence-based decisions in eggplant cultivation. Plant breeders and agronomists may use these insights to better align hybrids with suitable production systems, while growers can refine input management so that resources are directed where the crop is physiologically able to make best use of them. Such physiology-based precision approaches are increasingly important in the current context, where high productivity must be achieved in parallel with environmental responsibility. In this sense, the outcomes of the present work contribute to the development of eggplant production systems that are, at the same time, productive, stable and environmentally sound.

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