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Combined Approach of Melatonin, Plant Growth-promoting Rhizobacteria, and Strigolactone in Mitigating Carbendazim-induced Stress in Chickpea (*Cicer arietinum* L.)

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Abstract

This study investigates whether plant growth-promoting rhizobacteria (PGPR), melatonin (MEL), and strigolactone (STR), alone or in combination, counteract carbendazim (CAR) induced stress and restore pigment integrity, electron transport efficiency, and redox and osmotic equilibrium in chickpea seedlings. Certified chickpea seeds (Punjab Agricultural University, India), *Pseudomonas putida* strain (MTCC3315), and CAR (0.6 mM; inhibitory concentration (IC_{50})). Surface-sterilized seeds were germinated for 10 days in Petri dishes (triplicate) under: Control, CAR, CAR + MEL, CAR + PGPR, CAR + MEL + PGPR, and CAR + MEL + PGPR + STR. PGPR was applied at 10^9 cells mL^{-1}. Growth traits (fresh/dry mass, radicle/plumule), photosynthetic pigments, secondary metabolites, osmolytes and reactive oxygen species (ROS) were quantified by standard spectrophotometry; effects were evaluated. Absorbance-based assays and biomass measurements were recorded on 10-day seedlings, with results expressed per unit fresh/dry weight (FW/DW). CAR severely suppressed pigments and reduced carotenoids. PGPR partially restored pigments; MEL + PGPR improved stability; the triple consortium showed the most recovery and maximized carotenoids. Flavonoids rose ~3-fold with MEL + PGPR, while anthocyanins were highest with PGPR alone. CAR elevated trehalose, glycine betaine (GB) and proline; consortia generally reduced trehalose/GB toward control, with nuanced proline responses. PGPR lowered superoxide anion relative to CAR, whereas the consortium constrained hydrogen peroxide (H_2O_2), indicating balanced signaling and detoxification. Bio-priming with *P. putida* augmented by MEL and STR substantially alleviates CAR stress by restoring photosynthetic pigments, re-tuning osmolytes and moderating ROS, offering an eco-friendly adjunct to chemical disease management in chickpea.

Keywords: Carbendazim, *Cicer arietinum*, Melatonin, Plant growth-promoting rhizobacteria, Reactive oxygen species, Redox homeostasis, Strigolactone

Introduction

Chickpea (*Cicer arietinum* L.), an essential legume belonging to the Fabaceae family, serves as a major source of food and nutrition worldwide [1]. It is highly susceptible to fungal phytopathogens, which can drastically reduce yield [2]. Fungicides are often applied to protect chickpea crops; however, their excessive or indiscriminate use deteriorates soil quality, reduces microbial diversity [3], and impedes essential soil enzyme activities [4]. Beyond its food value, chickpea improves soil fertility in arid and rainfed regions through nitrogen fixation in symbiosis with rhizobia [5, 6].

A wide range of approaches has been developed to address global food insecurity caused by rapid population growth and limited agricultural land. To prevent substantial yield losses from pest infestations, farmers frequently use pesticides

[7]. These chemicals offer an efficient means of managing insect populations that threaten productivity [8]. Although pesticide use has enhanced crop yields and food availability, it also represents a growing dependence on synthetic chemicals, raising serious concerns about their long-term effects on human health and the environment. The increasing reliance on hazardous pesticides poses major ecological threats [9].

CAR, a systemic fungicide, is commonly applied in agriculture, forestry, and veterinary practice to manage fungal infections. Despite its effectiveness, its extensive use raises sustainability and ecological concerns [10]. A benzimidazole derivative, CAR protects cereals, oilseed rape, fruits, vegetables, and ornamentals from fungal diseases [11]. Its broad use underscores the heavy dependence on chemical control in modern farming [12]. Chemically known as methyl-1H-benzimidazol-2-ylcarbamate (MBC; $C_9H_9N_3O_2$), CAR demonstrates wide-spectrum fungicidal properties [13]. However, it can cause severe toxicity in living organisms, including infertility, embryonic malformations, liver damage, apoptosis, hormonal disruption, and genetic mutations [14].

Residues of CAR often remain on plant surfaces or are absorbed and stored within tissues, potentially accumulating along the food chain. Even low concentrations can disrupt hormonal balance and damage the liver and reproductive organs in mammals [15]. Hence, minimizing CAR residues in food crops is essential for ensuring human and environmental safety. Pesticide accumulation negatively affects food quality by inducing oxidative stress, suppressing plant growth, impairing photosynthetic performance, and generating ROS [16]. Plants counter this toxicity through enzymatic and non-enzymatic detoxification mechanisms.

PGPR are beneficial soil microorganisms that enhance plant development under stress conditions by improving nutrient availability, producing phytohormones, degrading organic matter, detoxifying xenobiotics, and suppressing pathogens [17, 18]. These bacteria contribute significantly to sustainable crop productivity, especially under agrochemical stress conditions. *C. arietinum* L. serves as an excellent model for studying plant responses to PGPR, MEL, and STR due to its well-documented stress physiology and signaling behavior [19].

Microorganisms have remarkable potential to biotransform pesticides, as soil microbial communities can rapidly break down diverse pesticide molecules [20]. PGPR not only improves nutrient uptake and biomass production but also strengthens plant tolerance mechanisms [21]. Among them, *P. putida* is particularly notable for its strong root colonization ability, hormone synthesis, and nutrient solubilization, enhancing plant resilience to various stresses [22]. It also mitigates ROS-induced oxidative damage [23].

Research indicates that *P. putida* effectively degrades CAR in soil and water, significantly reducing its residue levels [10]. The bacterium demonstrates high tolerance and efficiency in bioremediation applications, converting toxic fungicide compounds into less harmful forms [24]. Consequently, pesticide-induced oxidative and physiological stress in chickpea can be alleviated through inoculation or external application of *P. putida*, making the integration of such plant-microbe systems a promising eco-friendly alternative to chemical remediation strategies.

Materials and Methods

Preparation of plant sample and biochemical analysis

A 500 mg plant sample was homogenized in 2 mL of 2 M trichloroacetic acid and centrifuged at 5,000 revolutions per minute (RPM) for 15 min at 4 °C. The supernatant (0.5 mL) was mixed with 0.5 mL of 10 mM potassium phosphate buffer and 1 mL of 1 M potassium iodide (KI) for H_2O_2 estimation [25].

Microbial strain maintenance and inoculation

P. putida strain (MTCC3315) obtained from Council of Scientific and Industrial Research-The Institute of Microbial Technology, Mohali, was revived in nutrient broth (50 mL) at 28 °C for 48 h. The culture was centrifuged at 4 °C for 20 min, washed with bi-distilled water, and standardized to 10^9 cells/mL [26].

Seed selection and germination

C. arietinum seeds were procured from Punjab Agricultural University, India. The variety was chosen for its strong germination rate, yield potential, and stress tolerance. CAR standard was obtained from Sigma-Aldrich, and CAR 75% water dispersible granule from ADAMA Ltd., Hyderabad. The working concentration (0.6 mM) was selected based on its IC_{50}. Sterilized Petri dishes lined with Whatman no. 1 filter paper pre-soaked in 0.6 mM CAR received surface-sterilized seeds followed by microbial inoculum (10^9 cells/mL) [27]. Treatments were maintained in triplicate for 10 days before harvesting.

Growth and photosynthetic trait analysis

Ten-day-old seedlings were analyzed for FW, DW, and total seedling balance [28]. Total chlorophyll (Chl), Chl-a and Chl-b, and carotenoids were measured spectrophotometrically (Shimadzu UV 1800). Plant tissue (200 mg) was homogenized in 4 mL of 80% acetone, centrifuged at 12,000 RPM for 20 min at 4 °C, and absorbance read at 645, 663, 480, and 510 nm [29, 30].

Anthocyanin and flavonoid estimation

Anthocyanin content was determined by grinding 0.35 g tissue in methanol hydrochloric acid mixture [31]. Absorbance at 530 and 657 nm was used to calculate anthocyanin concentration. For total flavonoids, 0.35 g tissue was extracted in methanol, centrifuged, mixed with sodium nitrite, aluminum chloride, and sodium hydroxide, and absorbance measured at 510 nm [32].

Osmolyte estimation

Trehalose was quantified in 80% ethanol extracts using anthrone reagent, measuring absorbance at 620 nm and expressed as mg/g DW [33]. GB content was estimated from samples incubated in toluene for 24 h, followed by extraction with 2 N solutions of hydrochloric acid and potassium triiodide. The pink organic layer's absorbance was read at 365 nm

[34]. Proline was determined using acid ninhydrin and toluene, measuring absorbance at 520 nm [35].

ROS measurement

Superoxide anion (O_2^-) content was measured from 500 mg tissue homogenized in phosphate buffer (pH 7.8, 65 mM) with 1% polyvinylpyrrolidone. The supernatant reacted with hydroxylamine hydrochloride and colorimetric reagents, and absorbance was read at 520 nm [36]. H_2O_2 concentration was expressed in µmol/g FW after reaction with KI, reading absorbance at 390 nm [25].

Results and Discussion

The findings provide a comparative analysis of most biochemical and physiological parameters of most of the combinations of treatments. Each comparison shall be classified as highly significant (HS), moderately significant, low significant and no significant (NS). The important comparisons are between CAR, MEL, PGPR, and STR (as compared to the control group) and amongst each other. The examples given in table 1 demonstrate that in spite of the modifications and adjustments, there were possibilities of finding a combination of alternative behavior strategies adequate to meet the health needs and demands.

The photosynthetic efficiency of *C. arietinum* seedlings exposed to CAR can be restored through exogenous application of MEL, PGPR, and STR. Photosynthetic parameters including total Chl, Chl-a, Chl-b, carotenoids, flavonoids, and anthocyanins were analyzed in the present study. CAR exposure caused severe suppression of pigments, with total Chl decreasing to ~0.004 mg g^{-1} FW compared to ~0.033 mg g^{-1} FW in control seedlings ($p < 0.05$), representing an ~88% reduction. Similarly, Chl-a and Chl-b declined by ~85 - 90% and ~83%, respectively (Figure 1).

Supplementation with MEL provided a modest recovery, slightly improving Chl-b but showing no significant repair of total Chl and Chl-a. PGPR inoculation enhanced pigment retention with values approaching those of control seedlings. MEL + PGPR supplementation further improved Chl stability, while the combined treatment with MEL+ PGPR + STR produced the most pronounced effect, significantly ($p < 0.05$) increasing total Chl (~0.025 mg g^{-1} FW), corresponding to

Figure 1: Comparative germination study of seed and initial growth of seedlings. **(A)** Isolated seedlings showing a variation in root elongation under different treatments (control/Mel/PGPR/STREG). **(B)** The individual seedlings in various conditions showing disparities in growth responses of the radicle and plumule length.

~70 - 75% recovery of both Chl-a and Chl-b compared to CAR-exposed seedlings.

Carotenoid content was reduced by ~50% under CAR treatment. MEL co-application partially restored carotenoids, while PGPR supplementation enhanced accumulation more effectively. The MEL + PGPR treatment increased carotenoids to ~0.012 mg g^{-1} FW, and the maximum content (~0.018 mg g^{-1} FW) was achieved with the triple treatment (STR + MEL + PGPR), showing significant ($p < 0.05$) recovery over CAR-exposed seedlings (Figure 2).

Anthocyanins exhibited a distinct pattern. CAR markedly reduced their levels, whereas both MEL and PGPR individually enhanced accumulation. However, MEL or MEL + PGPR resulted in lower anthocyanin content than PGPR alone, and the triple treatment produced only minimal change compared to PGPR.

Flavonoid levels remained largely unaffected under CAR stress. Neither MEL nor PGPR alone induced significant increases. However, the combined MEL + PGPR treatment elevated flavonoids nearly three-fold (~0.18 mg g^{-1} FW) compared with the control, while the triple treatment (MEL + PGPR + STR) further improved recovery ($p < 0.05$).

Osmoprotectants

Exogenous addition of MEL, PGPR, and STR affect accretion of osmoprotectants in chickpea seedlings subjected to CAR.

Table 1: Comparison of treatment means using one way analysis of variance, indicating significant differences ($p < 0.05$).

Parameters	Control vs CAR	Control vs CAR + MEL	Control vs CAR + PGPR	Control vs CAR + MEL + PGPR	Control vs CAR + STGR + MEL + PGPR
Total Chl	0.02913 HS	0.03010 HS	0.02807 HS	0.02587 HS	0.008467 HS
Chl-a	0.02427 HS	0.02530 HS	0.02243 HS	0.02293 HS	0.01097 HS
Chl-b	0.009133 HS	0.01003 HS	0.01150 HS	0.004800 HS	0.002633 HS
Carotenoids	0.005067 HS	0.004500 HS	0.0007667 HS	-0.001333 HS	-0.007767 HS
Flavonoid	-0.01180 NS	-0.000800 NS	0.01887 HS	-0.1268 HS	-0.01113 NS
Anthocyanin	0.3425 NS	-2.147 HS	-3.509 HS	-0.6605 NS	-0.02493 NS
Trehalose	-1.164 HS	-1.007 HS	-1.260 HS	-1.233 HS	-0.5105 HS
Proline	-1.363 HS	-0.2723 HS	-0.7040 HS	0.002667 NS	-1.789 HS
GB	0.01097 HS	-0.3274 HS	-0.04437 HS	-0.2574 HS	-0.08770 HS
Superoxide anion	-0.04120 HS	-0.3735 HS	-0.1665 HS	-0.1055 HS	-0.1545 HS
H_2O_2	0.01773 HS	-0.04227 HS	-0.1896 HS	-0.2336 HS	-0.2109 HS

Figure 2: Comparative evaluation of photosynthetic pigments, osmoprotectant accumulation, and ROS generation in *C. arietinum* seedlings subjected to CAR stress and associated mitigation treatments. Data are expressed as mean ± SD, and statistically significant variations among treatments ($p < 0.05$) are denoted by distinct lowercase letters.

Osmoprotectant levels were determined such as trehalose, GB and proline to determine the response of stress under CAR exposure. CAR treatment further enhanced the abundance of trehalose (~1.85 mg g^{-1} FW), GB (~0.025 mg g^{-1} FW), and

proline, which confirmed their contribution to osmotic adjustment and stress tolerance. MEL supplement significantly ($p < 0.05$) raised the GB (~0.36 mg g^{-1} FW; ~15 fold compared to CAR alone) and reduced slightly the trehalose levels. The trehalose content of litter seedlings remained high, and GB (GB ~0.08 mg g^{-1} FW) was marginally increased in PGR inoculation as compared to CAR-stressed seedlings. The combined treatment of MEL + PGPR led to a further decrease in levels of trehalose and GB, whereas the triple treatment (MEL + a further decrease in levels of trehalose and GB, whereas the triple treatment (MEL + PGPR + STR) recorded the lowest levels of trehalose (~1.2 mg g^{-1} FW) and GB (~0.12 mg g^{-1} FW), indicating the decrease in severity of stress and consequently the decrease in osmolyte requirements. Regarding proline, CAR exposure led to a high induction whereas MEL, PGPR and their combination remarkably ($p < 0.05$) reduced its accumulation. Interestingly, the triple treatment yielded highest proline levels, which is universal in terms of adaptive in the extreme stress conditions (Figure 2).

ROS dynamics (Superoxide and H_2O_2)

CAR stimulates oxidative bursts and MEL, PGPR, and STR modulate the level of ROS in chickpea seedlings differently.

The superoxide anion and H_2O_2 contents were used to estimate regulation of oxidative burst under CAR stress and supplementation with MEL, PGPR, and STR. Compared to control seedlings, car exposure increased the levels of superoxide modestly, but when combined with MEL, superoxide production was greatest (~3.4-fold compared to control; $p < 0.05$). Compared to CAR, PGPR treatment alleviated superoxide production, as has been reported a result of integrated stress response-mediated detoxification. The H_2O_2 levels exhibited a comparable trend where MEL increased levels by approximately 90% compared to the control and PGPR increased levels nearly 5-fold compared to CAR-stressed seedlings. H_2O_2 accumulation was also taken up significantly (~300% increase above CAR; $p < 0.05$) by the MEL + PGPR treatment, signifying a pre-conditioned signaling state. The effectiveness of supplementing STR was that levels of H_2O_2 did not peak above 0.26 mg g^{-1} FW, indicating a balance between detoxification and oxidative signaling, but not them (Figure 2).

Exposure to CAR resulted in severe impairment of growth and metabolic functions in *C. arietinum* seedlings, which were prominent in the significant reduction of photosynthetic pigments. Figure 2 illustrates that total Chl, Chl-a, and Chl-b dropped by almost 85 - 90%, indicating how susceptible the photosynthetic apparatus is to oxidative stress induced by fungicides. The reductions are consistent with previous observations that attribute pigment loss to oxidative degradation, reduction of Chl synthesis, and activation of chlorophyllase [37]. MEL treatment delayed pigment degradation and preserved thylakoid integrity, but its protective effect was limited despite some stabilization [38, 39]. PGPR inoculation was more efficient, possibly due to its potential to improve nutrient uptake, hormonal balance, and photosynthetic activity [40]. The triple treatment of MEL, PGPR, STR restored pigments most efficiently, which indicates synergistic interactions between MEL ROS-scavenging, PGPR's growth-promoting, and STR photosynthesis-regulating properties [41, 42]. In addition, under CAR stress, carotenoid concentration decreased, limiting photoprotective potential. While PGPR elicited a higher recovery, indicating its role in secondary metabolism and nutrient mobilization, MEL only partially restored carotenoids [43]. The triple therapy achieved near-complete restoration, which is consistent with STR-mediated regulation of pigment biosynthesis. The combined treatments further increased carotenoid accumulation. However, anthocyanins displayed a clear pattern: MEL and PGPR separately increased accumulation, although CAR decreased their levels. Yet, their combined and triple treatments did not sustain this increase, indicating that antioxidant protection may shift from anthocyanins to carotenoids and enzymatic systems under integrated defensive responses. CAR and solo treatments had no effect on flavonoids, but combined treatments significantly increased them, indicating a reprogramming of phenylpropanoid metabolism mediated by STR to boost antioxidant defenses.

In parallel, CAR strongly induced osmoprotectants such as proline, GB, and trehalose, reflecting classical stress adaptation strategies. As MEL modulates osmotic adjustment pathways, it suppressed trehalose and diverted osmolyte accumulation toward GB [44]. While the triple treatment significantly reduced both trehalose and GB, PGPR maintained high trehalose and marginally boosted GB, indicating that combination protection alleviated the severity of stress and decreased the need for osmotic adjustments. However, proline accumulation remained high even after the triple treatment, confirming its ubiquitous function as a redox buffer and compatible solute under stress [45].

Oxidative stress indicators further indicated variable responses across treatments. Superoxide and H_2O_2 levels were slightly elevated by CAR, while MEL unexpectedly increased ROS levels, confirming its dual function as an antioxidant and pro-oxidant based on concentration and stress level [38]. Consistent with its capacity to create induced systemic resistance [46], PGPR markedly decreased ROS accumulation. The triple treatments and the combined MEL + PGPR maintained high H_2O_2 levels (Figure 2), indicating that ROS were not only harmful byproducts but also crucial signaling molecules in defense regulation [47]. These findings highlight that the integrated treatment with MEL, PGPR, and STR offered the best mitigation, even though CAR significantly disturbed pigment metabolism, osmotic balance, and redox homeostasis. These bio stimulants worked in concert to provide a multi-layered protective approach that included secondary metabolism reprogramming, osmolyte regulation, pigment stabilization, and ROS signaling. Such integrative approaches hold strong potential for sustainable crop protection against fungicide-induced stress.

Conclusion

Based on the present research, CAR has adverse effects on the photosynthetic pigment content and growth attributes of chickpea seedlings that generate a high level of ROS and cause profound imbalanced redox. Nevertheless, the supplementation of *P. putida* and plant growth regulators, including MEL and STR, enhances the plant defense system in terms

of subsequent elevation of ROS scavenging antioxidative enzymes and antioxidants. CAR also induces accumulation of osmolytes, which is further enhanced by the presence of *P. putida* on the same, in order to alleviate oxidative stress in chickpea seedlings. Finally, *P. putida* shows great capacity to relieve the stress caused by CAR. Therefore, the external application of *P. putida* with PGRs may be of interest in the management of pesticide-related stress through an agronomic point of view. Considering the controversies over toxicity of pesticides in agricultural products, effort should be directed at tackling this menace. Subsequent studies with biotechnological and genetic methods may reveal the system behind *P. putida* induced tolerance to CAR.

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Conflict of Interest

None.

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