Plant Archives Vol. 26, No. 2, 2026 pp. 2817-2828 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.387

PINK-PIGMENTED FACULTATIVE METHYLOTROPHS IN DROUGHT STRESS MITIGATION: PLANT GROWTH-PROMOTING MECHANISMS AND THEIR PROSPECTS IN OKRA

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(Date of Receiving-04-18-2026; Date of Revision-15-10-2026; Date of Acceptance-20-10-2026)

ABSTRACT

Pink-pigmented facultative methylotrophs (PPFMs), represented mainly by members of *Methylobacterium* and *Methylorubrum*, are widely associated with the phyllosphere of plants. Their ability to utilise plant-derived methanol and express diverse plant growth-promoting traits has increased interest in their role in plant growth and stress tolerance. PPFMs can produce or influence phytohormones, regulate ethylene through ACC deaminase, mobilise nutrients and contribute to plant antioxidant defence. These activities can influence root development, nutrient acquisition, water relations, photosynthetic performance and cellular protection under adverse conditions. Increasing evidence from different crop systems suggests that PPFM-mediated responses may contribute to tolerance to drought and other abiotic stresses through coordinated changes in plant physiology and biochemistry.

This review examines the major plant growth-promoting traits of PPFMs and their possible roles in abiotic stress mitigation, with particular emphasis on drought. The physiological and biochemical responses associated with PPFM-mediated stress tolerance are discussed. Information on PPFM associations with okra and their potential role in improving drought tolerance in this crop remains limited. This knowledge gap is important because drought can adversely affect growth, flowering and pod development in okra. Evidence from different crop systems is integrated to identify mechanisms that may be relevant to okra, while recognising the limited direct evidence available for this crop.

Key words : Methylotrophy, Phytohormones, ACC deaminase, Siderophores, Antioxidant defence, Plant–microbe interactions.

Introduction

Okra (*Abelmoschus esculentus* L. Moench) belongs to the family Malvaceae and is grown widely across tropical and subtropical regions for its tender green pods. The crop suits smallholder vegetable systems well, since its short duration and repeated harvests support both household nutrition and regular market income. Okra pods carry dietary fibre, mucilage, minerals and bioactive compounds, and recent pharmacological work has drawn attention to their role in glycaemic regulation and antioxidant activity (Mokgalaboni *et al*., 2023; Ahmad *et al*., 2025). Breeding and management priorities have shifted accordingly. Yield still matters, but stress resilience and efficient water use now sit alongside it as improvement targets (Lata *et al*., 2025).

Unlike crops harvested once, okra grows and flowers continuously through much of its cycle, so stress at any single stage can carry forward and reduce later flushes of flowers and pods. Water availability has a direct effect on okra growth and pod development. Water shortage during the early growth period can limit canopy development. If the stress occurs around flowering, pollen viability, fruit set and subsequent pod growth may be affected. Stress during pod development can further reduce pod size and quality. The effect of drought depends greatly on when the plant experiences water deficit.

Understanding these responses is important for evaluating approaches that can help okra plants withstand periods of limited water availability.

Pink-pigmented facultative methylotrophs (PPFM) are plant-associated bacteria commonly found on leaves and around roots. Many PPFM can use methanol released from pectin degradation of plant tissues as a carbon source. They have also been reported to produce compounds involved in plant growth, ethylene regulation, nutrient acquisition and antioxidant defence. These properties have attracted interest in their use as beneficial bacteria under environmental stress. In drought conditions, such effects could help maintain plant water status, root growth and cellular protection. The available evidence on PPFM and drought responses can provide a basis for assessing their potential in crops such as okra.

Drought Stress in okra : Physiological consequences

Drought is not a single event but a progressive restriction that begins in the root zone and spreads through the plant. Cellular hydration, carbon assimilation and nutrient transport all come under pressure as water becomes limiting. Leaf expansion slows and stomata close early, while beneath these visible symptoms drought disturbs photosynthetic electron transport, membrane stability and reproductive development. Plants respond through coordinated changes in root growth, osmotic adjustment, antioxidant defence and hormone signalling, with abscisic acid, ethylene and auxin all playing distinct roles (Chae *et al*., 2007; Farooq *et al*., 2009).

Drought tolerance is a complex response influenced by genotype, plant developmental stage and the duration of stress. As carbon fixation declines under water deficit while light absorption continues, the imbalance can increase the formation of reactive oxygen species. Their accumulation can damage membrane lipids, proteins and nucleic acids when antioxidant protection is insufficient (Apel and Hirt, 2004; Mittler, 2002). Enzymes such as superoxide dismutase, catalase and ascorbate peroxidase, together with non-enzymatic antioxidants such as ascorbate and glutathione, help maintain cellular redox balance. The efficiency of this antioxidant system can influence the extent of drought injury.

Drought also alters the balance between root and shoot growth. A moderate reduction in shoot growth may help conserve water by reducing transpirational demand. Severe water deficit can restrict photosynthesis and reduce assimilate production. Under moderate stress, plants allocate relatively more growth to roots, allowing greater exploration of deeper soil layers. Prolonged or severe dehydration can suppress root growth as well. Drought tolerance is thus better assessed using a combination of traits, such as root development, relative water content, chlorophyll stability, membrane integrity and yield retention, rather than biomass alone (Mittler *et al*., 2004).

Okra tolerates warm conditions reasonably well, but pod formation and marketable yield fall sharply when moisture stress coincides with active vegetative growth, flowering or fruit development. Water deficit lowers leaf water content, disturbs photosynthesis and shrinks pod elongation. Combined heat-drought stress affects photosynthetic efficiency, chlorophyll traits, electrolyte leakage and biomass accumulation in okra, while tolerant genotypes hold onto better photosystem performance (Mkhabela *et al*., 2023; Opoku *et al*., 2024). Root plasticity and xylem adjustment also contribute to seedling-stage resilience in okra (Kaur *et al*., 2025).

The harvested organ is a rapidly elongating immature pod carrying high water content, which makes okra unusually sensitive to anything limiting cell expansion or carbohydrate flow into developing fruit. Reduced turgor restricts pod elongation directly, while lower stomatal conductance cuts the carbon assimilation needed to sustain repeated harvest. Because pods are picked frequently, drought's cumulative cost shows up as fewer harvestable pods, shorter pods and earlier fibre development, all with direct consequences for commercial production.

Pink Pigmented facultative Methylotrophs: A Functional overview

PPFM are aerobic, Gram-negative bacteria represented chiefly by *Methylobacterium* and *Methylorubrum*, distinguished by pink to orange carotenoid pigmentation and the capacity to grow on one-carbon compounds (Anthony, 1982; Patt *et al*., 1974). Their facultative methylotrophic habit lets them use methanol released during pectin demethylation in expanding cell walls, giving them a durable ecological foothold on leaf surfaces (Green, 1992; Holland and Polacco, 1992). Methanol oxidation runs through pyrroloquinoline quinone-dependent methanol dehydrogenase, with the large subunit encoded by *mxaF*, now used as a functional marker across methylotrophic bacteria (Anthony *et al*., 1994; McDonald and Murrell, 1997).

PPFM occur across the phyllosphere, rhizosphere and endosphere. They are more dominant in the phyllosphere since leaves continuously release methanol and other low molecular weight compounds (Corpe, 1985;

Wellner *et al*., 2011). Reports across vegetables, cereals and horticultural crops confirm the association is frequent and ecologically stable (Balachandar et al., 2008). Genetic diversity within plant-associated isolates is considerable, and native strains adapted to a specific host or field may persist and function better than introduced cultures under real growing conditions (Alessa *et al*., 2021).

Plant Growth-promoting traits of PPFMs Associated with Drought Stress Tolerance

Growth promotion mediated by PPFM is multifactorial, arising from the combined expression of several functional traits rather than a single dominant mechanism. These bacteria synthesize phytohormones, regulate ethylene levels through ACC deaminase activity, mobilize soil nutrients and secrete metabolites that influence host physiology. The relative contribution of each trait is not fixed; it varies with bacterial strain, host genotype, inoculation method and prevailing environmental conditions. Screening native isolates for a specific crop therefore remains essential, since PPFM efficacy cannot be assumed to transfer uniformly across hosts or growing conditions.

Indole-3-acetic acid and root architecture

IAA regulates cell division, cell elongation, vascular differentiation and lateral root initiation. Plant-associated bacteria synthesize it mainly through tryptophan-dependent routes, and aerobic methylobacteria release measurable auxin into culture media, with production increasing when tryptophan is supplied as precursor (Ivanova *et al*., 2001; Omer *et al*., 2004).

The physiological payoff of bacterial IAA lies mostly in root system expansion. A larger absorptive root surface improves water and nutrient acquisition especially when moisture is limited. PPFM from vegetables and cereal crops have shown strain-dependent IAA production tied to better germination and root growth (Lee *et al*., 2004; Gayan *et al*., 2023). Okra depends heavily on early root establishment for later performance under intermittent drought, so IAA-producing native PPFM support drought tolerance through a deeper or more branched root system.

High levels of bacterial IAA production may inhibit primary root elongation, whereas moderate levels can promote lateral root formation and root hair development. Greater lateral branching may help plants exploit moisture in the upper soil layers following limited irrigation. The deeper axial root growth will be more advantageous as soil moisture declines. The relative benefit of these root responses will depend on soil characteristics and irrigation conditions. Hence PPFM isolates should not be selected solely on the basis of their maximum IAA production.

Gibberellins and controlled shoot development

Gibberellins influence germination, stem elongation and mobilization of stored reserves. Bacterial GA production occurs across several plant-associated microorganisms including methylotrophs, and reported output varies substantially among PPFM strains from different crop phyllospheres (Radha, 2007; Gayan *et al*., 2023).

Balanced gibberellin activity can support seedling emergence and dry matter accumulation without pushing water use too high (Atzorn *et al*., 1988; Saleem *et al*., 2015). Okra needs reasonably rapid canopy development to support pod yield, yet excessive vegetative growth intensifies water demand, so screening for moderate rather than maximal GA output is the more defensible strategy.

Cytokinins and delayed senescence

Cytokinins govern cell division, chloroplast development, nutrient mobilization and the timing of leaf senescence. Several *Methylobacterium* strains synthesize cytokinin-like compounds, with tRNA degradation proposed as one source of the secreted signal (Ivanova *et al*., 2000; Long, 2000). This activity may contribute to the improved leaf expansion and chlorophyll retention observed following PPFM inoculation in other crops.

Cytokinin balance is important under drought, since water deficit typically speeds up senescence and shrinks photosynthetic leaf area. Endosymbiotic *Methylobacterium oryzae* eased the impact of limited water availability in lentil by raising plant cytokinin levels, showing methylotroph-driven hormone modulation can influence drought tolerance beyond simple growth stimulation (Jorge *et al*., 2019). Cytokinin also interacts with auxin to shape root architecture (Aloni *et al*., 2006), so PPFM producing both hormones together may support shoot maintenance and root plasticity at once. The potential benefit may lie in moderating the rate of senescence rather than preventing it completely, since some degree of developmental adjustment can help the plant cope with stress. In okra, maintaining functional leaves is important for continued photosynthesis and assimilate supply to developing pods.

ACC deaminase and ethylene regulation

ACC deaminase lowers the pool of 1-aminocyclopropane-1-carboxylate, the immediate precursor of ethylene. Drought induces plants to overproduce ethylene, which restricts root elongation and speeds senescence. Bacteria carrying ACC deaminase

cleave ACC into ammonia and alpha-ketobutyrate, removing substrate from the ethylene pathway and helping the plant sustain growth under adverse conditions (Glick, 1995; Glick *et al*., 1998; Saleem *et al*., 2007).

This activity has been confirmed in several methylotrophs, including *Methylobacterium fujisawaense*, *M. oryzae* and *M. radiotolerans* (Madhaiyan *et al*., 2006; Fedorov *et al*., 2013; Kwak *et al*., 2014). ACC deaminase-positive epiphytic methylobacteria lowered ethylene levels and improved root and shoot growth in rice and tomato seedlings (Chinnadurai *et al*., 2009) and screening of isolates from tea and banana confirms the trait is widespread but strain-dependent (Senthilkumar *et al*., 2021; Marimuthu *et al*., 2023). A recent review of bacterial ACC deaminase reinforces its role in reducing ethylene-mediated growth inhibition under water deficit (Shahid *et al*., 2023). For drought-stressed okra, improved root elongation and delayed stress ethylene through this pathway carry direct implications for survival and yield retention.

Phosphate solubilization under moisture limitation

Soil phosphorus is essential for energy transfer, nucleic acid synthesis and root development, yet much of it is unavailable as insoluble phosphates. Phosphate-solubilizing microorganisms release fixed phosphorus through organic acid secretion, acidification and enzymatic mineralization. Several aerobic methylobacteria solubilize mineral phosphates (Jones *et al*., 2007; Agafonova *et al*., 2013) and genome data from *M. oryzae* shows genes tied to phosphate release from organic and inorganic sources (Kwak *et al*., 2014).

As soil dries, phosphorus movement through the soil solution becomes slower, which can limit its availability to plant roots. PPFM isolates that can both promote root growth and improve phosphate solubilization will provide an advantage under drought. This combined effect could be important in vegetable crops, where rapid growth requires a continuous supply of nutrients even under limited soil moisture.

Nitrogen Acquisition and PPFM-mediated drought tolerance

Selected methylotrophic bacteria fix nitrogen; the discovery that *Methylobacterium* can nodulate legumes broadened the ecological role of this group well beyond phyllosphere colonization (Sy *et al*., 2001; Jourand *et al*., 2004). For a non-leguminous crop like okra, the practical value of nitrogen-fixing or ammonia-producing PPFM more likely comes from localized nitrogen enrichment and improved seedling vigour than from symbiotic nodulation. Drought commonly restricts nitrogen uptake by limiting mass flow and root activity, so isolates offering nitrogen-related support may help sustain chlorophyll and biomass under moisture stress (Senthilkumar *et al*., 2002; Lee *et al*., 2006).

Siderophore production

Siderophores, low molecular weight iron chelators secreted under iron limitation, improve microbial competitiveness in the rhizosphere and can restrict pathogen growth by starving competitors of accessible iron (Glick, 1995; Berg, 2009). PPFM isolates producing siderophores and other protective metabolites have been reported to suppress pathogens (Savitha *et al*., 2015; Gamit *et al*., 2023). Drought weakens host resistance to opportunistic pathogens, so siderophore-producing PPFM may support drought-stressed okra indirectly, through disease suppression and improved micronutrient acquisition.

Physiological and Biochemical Mechanisms of PPFM-mediated Drought Mitigation

Drought mitigation by PPFM is best understood as the combined outcome of several interacting mechanisms rather than the effect of one bacterial trait. These bacteria colonize leaf surfaces, roots and internal tissues, using plant-derived methanol for growth while releasing metabolites that shape host physiology in return. Their localization on the leaf surface is particularly relevant under drought, as leaves are among the first plant organs to experience changes in water status and increased oxidative stress. An active PPFM population on the phyllosphere may interact with the plant during the early stages of stress and influence subsequent physiological responses (Corpe, 1985; Wellner *et al*., 2011).

The hormonal contribution runs through most of this effect. Auxin-producing isolates increase root branching, improving access to residual soil moisture. Cytokinin-producing strains delay drought-induced senescence and preserve active leaf area. Gibberellin-producing strains, at balanced output, support early seedling establishment (Ivanova *et al*., 2000; Aloni *et al*., 2006; Jorge *et al*., 2019). The resulting growth response goes beyond a simple increase in biomass; it reorganizes plant architecture and metabolic activity in ways that support better performance when water is scarce.

Ethylene regulation through the activity of ACC deaminase offers plants an important mechanism for coping with stress. When water availability declines, plants increase the synthesis of ACC, which in turn drives higher ethylene production. Elevated ethylene levels, however,

Table 1 : Plant growth-promoting traits reported in PPFMs.

PPFM trait	Functional role	Plant-associated evidence	Representative references
IAA production	Modifies root architecture, cell expansion and vascular development; may improve water and nutrient acquisition.	PPFM isolates with IAA production have been associated with improved germination, seedling vigour and root growth.	Ivanova *et al*. (2001), Lee *et al*. (2004), Nysanth *et al*. (2023), Gayan *et al*. (2023)
Gibberellin-related activity	Supports germination, elongation and early establishment when activity is physiologically balanced.	Gibberellin-producing methylotrophs have been reported from several crop-associated isolates.	Anurajan (2003), Radha (2007), Savitha *et al*. (2013), Gayan *et al*. (2023)
Cytokinin production/ activity	Supports cell division, chloroplast maintenance and delayed senescence.	*Methylobacterium* spp. can produce cytokinin-related compounds; M. oryzae has been linked with altered cytokinin status under water limitation.	Ivanova *et al*. (2000), Long (2000),
ACC deaminase	Reduces stress-associated ethylene formation and can support root growth during adverse conditions.	Activity reported in several Methylobacterium species and in plant-associated isolates.	Madhaiyan *et al*. (2006), Fedorov *et al*. (2013), Kwak *et al*. (2014), Marimuthu *et al*. (2023), Manju Bhargavi (2024)
Phosphate mobilization	Improves access to phosphorus needed for energy metabolism, root development and membrane function.	Phosphate-solubilizing and phosphatase-associated functions have been reported in methylotrophs.	Jones *et al*. (2007), Agafonova *et al*. (2013), Kwak *et al*. (2014)
Nitrogen-related functions	May contribute to nitrogen acquisition or localized N enrichment in compatible plant associations.	Nitrogen fixation and nifH-associated functions occur in selected methylotrophs; the trait is strain dependent.	Sy *et al*. (2001), Jourand *et al*. (2004, 2005)
Siderophore production	Improves iron competition and can contribute to indirect disease suppression.	Siderophore and secondary metabolite production has been reported in plant-associated methylotrophs.	Savitha *et al*. (2015), Gamit *et al*. (2023), Yaralagadda Manju Bhargavi (2024)

can become detrimental—limiting root growth and accelerating senescence. By moderating this pathway, ACC deaminase helps balance ethylene output, supporting healthier root development and delaying premature aging under drought conditions. ACC deaminase-positive methylotrophs shrink the ACC pool available for ethylene formation, letting root growth continue and delaying the effects of ethylene (Glick *et al*., 1998; Madhaiyan *et al*., 2006; Chinnadurai *et al*., 2009). Sustained root activity through this mechanism determines both water uptake during stress and the speed of recovery after rewatering.

Water relations and relative water content

Relative water content, RWC, is a widely used indicator of plant water status because it reflects the balance between root uptake and transpirational loss. Genotypic differences in RWC maintenance have long distinguished drought-tolerant plants from susceptible ones (O'Toole and Moya, 1978). PPFM inoculation has improved RWC under stress in tomato, pointing to a real influence on how efficiently the plant retains or uses available water (Kumar *et al*., 2017; Sivakumar *et al*., 2017).

Relative water content (RWC) alone provides only a partial view of plant water status, as it integrates multiple physiological and structural determinants. Leaf anatomy, root hydraulic conductance, and osmotic adjustment all contribute to the maintenance of RWC. A plant may sustain RWC through early stomatal closure, enhanced water uptake, or solute accumulation that preserves cellular hydration—each strategy carrying distinct agronomic trade-offs. Consequently, interpreting RWC in PPFM-treated okra is most meaningful when considered alongside photosynthetic performance, root traits, and yield outcomes, rather than in isolation.

Membrane stability and Cellular Protection under Drought stress

Cell membrane stability offers another useful physiological index of drought tolerance. Dehydration and oxidative stress disturb membrane lipids and proteins, leaking electrolytes out of cells. Sullivan first proposed electrolyte leakage as a stress-screening method in 1972, and later work confirmed its value for drought and heat tolerance screening across crops (Blum and Ebercon, 1981; Premchandra *et al*., 1990). Higher membrane stability under drought generally reflects better protection of the lipid bilayer, usually through osmolyte accumulation and reduced lipid peroxidation working together.

Rice plants treated with *Bacillus altitudinis* FD48 and *Methylobacterium* spp. held higher membrane stability than untreated drought-stressed controls (Kumar *et al*., 2017), and similar improvements followed PPFM-mediated antioxidant enhancement in tomato and snap bean (Chandrasekaran *et al*., 2017; Gawad *et al*., 2015). Membrane stability could serve okra research well as a practical index for testing whether native PPFM isolates protect cellular integrity once drought sets in.

Chlorophyll retention and photosynthetic performance

Water deficit reduces chlorophyll content through impaired biosynthesis, faster degradation and oxidative damage to chloroplast structures, cutting light-harvesting capacity and photosynthesis with it. Methylotrophic inoculation has raised total chlorophyll content and photosynthetic performance in rice, soybean, chilli and tomato (Madhaiyan *et al*., 2004; Raghavendra and Santhosh, 2019). This matters directly for okra, since pod filling depends on a steady assimilate supply from functioning leaves.

Chlorophyll stability alone does not ensure productivity unless retained pigment remain integrated to functional electron transport, so SPAD readings work best alongside gas exchange or fluorescence measurements. Okra studies assessing gas exchange and fluorescence directly reinforce this point, showing that functional photosynthetic tolerance matters more than visual greenness alone (Mkhabela *et al*., 2023; Opoku *et al*., 2024).

Stomatal behaviour establish the immediate balance between conserving water and fixing carbon. Closure protects leaf water status, but prolonged closure limits the availability of carbon dioxide for photosynthesis. Root growth, osmotic adjustment and hormonal balance can moderate this trade-off and PPFM may contribute indirectly through auxin-mediated root development, cytokinin-related delay of senescence and ACC deaminase-mediated reduction of stress ethylene (Aloni *et al*., 2006; Madhaiyan *et al*., 2006). Sustaining pod production through intermittent dry spells in okra depends on holding this balance for as long as possible.

PPFM-induced Antioxidant Responses under Drought stress

Reactive oxygen species production overtakes cellular scavenging capacity as drought deepens, and chloroplasts, mitochondria and membrane-associated oxidases all contribute to this rise once photosynthetic electron transport becomes restricted (Apel and Hirt, 2004; Mittler *et al*., 2004). The enzymatic defense system is initiated by superoxide dismutase, which converts superoxide radicals into hydrogen peroxide. This intermediate is subsequently detoxified by catalase and ascorbate peroxidase, while glutathione reductase sustains the reduced glutathione pool required for the ascorbate–glutathione cycle (Foyer and Halliwell, 1976; Mittler, 2002). Stronger antioxidant enzyme activity under drought correlates with better membrane stability and less lipid peroxidation across several crops (Sharma and Dubey, 2005; Sandhya *et al*., 2011).

PPFM strengthen antioxidant defence directly through their own protective enzymes and indirectly by inducing host antioxidant systems. Elevated catalase, peroxidase and superoxide dismutase activity have been detected following PPFM treatment in stressed crops (Gawad *et al*., 2015; Kumar *et al*., 2017). The methylotrophic bacteria activate enzymatic and non-enzymatic antioxidant components together, cutting ROS damage under drought (Krishnamoorthy et al., 2021). Measuring antioxidant enzyme activity after PPFM inoculation in okra would clarify whether drought mitigation here runs mainly through improved redox regulation.

Osmolyte accumulation

Compatible solutes such as proline and soluble sugars accumulate in the cytoplasm during drought, adjusting osmotic potential and stabilizing proteins and membranes without disrupting normal metabolism even at high concentration (Hoekstra *et al*., 2001). Proline carries particular weight, since it also scavenges reactive oxygen species and may serve as a carbon and nitrogen reserve during recovery (Alia *et al*., 1993).

Foliar PPFM application raised proline accumulation alongside relative water content and photosynthetic rate in tomato under drought (Chandrasekaran *et al*., 2017; Sivakumar *et al*., 2017), and comparable effects on compatible solutes have been documented with other plant

growth promoting bacteria under moisture stress. Osmolyte accumulation likely matters most in okra during flowering and pod development, the stages when dehydration most quickly cuts into cell expansion and assimilate movement.

Evidence Across crops and the Gap in okra

Field results across several crops support these mechanisms. Combined application of drought-tolerant bacteria and methylotrophs improved membrane stability and relative water content in rice under water deficit (Kumar *et al*., 2017). Foliar PPFM application in tomato improved root traits, stress tolerance index and catalase activity under drought (Chandrasekaran *et al*., 2017; Sivakumar *et al*., 2018). Integrating PPFM with organic amendments improved chlorophyll stability and productivity in cotton under moisture stress (Kannan *et al*., 2019). These outcomes tend to be most consistent when the hormonal, osmoprotective, and antioxidant benefits conferred by PPFM are integrated with sound agronomic management practices. In such cases, the physiological support provided by PPFM complements management-driven resilience, resulting in more reliable improvements in crop performance.

In vitro screening using polyethylene glycol shows that methylotrophic isolates differ widely in their capacity to grow under osmotic stress, and only selected strains show adequate growth at severe water potentials (Jorge *et al*., 2019; Sharath *et al*., 2021). A recent black pepper study from Kerala found that selected PPFM isolates improved rooting, membrane integrity and antioxidant enzyme activity during drought stress (ManjuBhargavi *et al*., 2024). An isolate that performs well under normal conditions can still fail to stay metabolically active once drought sets in, so selecting native PPFM for okra needs to weigh both growth promoting function and intrinsic osmotic stress tolerance.

Recent reviews describe drought mitigation by methylotrophs as involving metabolic priming alongside direct growth promotion, so that plants respond faster once water deficit begins even without large differences under non-stress conditions (Gamit *et al*., 2023; Zhang *et al*., 2021). Evaluation protocols for okra need to include both normal and drought-stressed conditions if growth promotion and stress mitigation are to be separated experimentally.

Direct evidence on native PPFM isolates in okra remains thin despite this broader picture. Okra carries real economic weight and shows clear physiological sensitivity to moisture limitation during vegetative growth, flowering and pod development. Yet, the majority of drought-related research on PPFM inoculation has focused on crops such as rice, tomato and cotton, leaving okra comparatively underexplored. How native PPFM isolates associated with okra tolerate osmotic stress, and how they influence okra physiology under drought, remain open questions. A strain effective in one host will not automatically colonize or express the same functional traits in another crop, and okra's continuous flowering habit and stage-specific vulnerability to drought make it a distinct case that general PPFM literature cannot fully answer.

Conclusion

PPFM are plant-associated bacteria able to produce phytohormones, regulate ethylene through ACC deaminase, solubilize nutrients and support plant performance under abiotic stress. Selected isolates improve growth, water relations, chlorophyll retention and osmotic adjustment under drought across several crops (Chandrasekaran *et al*., 2017; Kannan *et al*., 2019; Marimuthu *et al*., 2023). Okra, given its continuous reproductive demand and acute sensitivity to moisture stress during flowering and pod fill, stands as a strong candidate crop for this kind of targeted evaluation. Closing the current evidence gap would give researchers and growers a clearer basis for using native PPFM isolates as a practical drought mitigation tool.

Acknowledgement

The authors sincerely thank Kerala Agricultural University, Thrissur, Kerala, India, for providing the academic environment and institutional facilities that supported the preparation of this review.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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