Beneficial Effects of Weed Endophytic Bacteria: Diversity and Potentials of Their Usage in Sustainable Agriculture

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Abstract

Plant growth-promoting endophytic bacteria dwell a relatively privileged niche within the host plants and confer beneficial effects to their hosts. These plant probiotics from weed species are poorly explored but possess the tremendous potentials for application in eco-friendly sustainable agriculture. Bacteria from diverse taxonomic genera such as *Sinorhizobium*, *Bacillus*, *Pseudomonas*, *Marinorhizobium*, *Sphingomonas*, *Sphingobium*, *Herbaspirillum*, *Micrococcus*, *Microbacterium*, and *Rhodococcus* are associated with weed species. Weed-originated plant growth-promoting bacteria (PGPB) exert beneficial effects to their host plants through fixation of atmospheric nitrogen and solubilization of insoluble essential mineral elements (e.g., phosphorus) produce phytohormones (e.g., indole-3-acetic acid), induce systemic resistance (ISR) response to hosts, and secrete antimicrobial substances and other metabolites to protect their hosts from biotic and abiotic stresses. The ISR have tied to disease resistance and abiotic tolerance of plants against drought, cold, salinity, and extreme temperature. As there is no comprehensive review on weed endophytes, this study reviews taxonomic diversity and beneficial effects of weed-associated bacteria and discusses how these natural bioresources could be utilized in agricultural productivity to a new dimension.

Keywords

Weed endophytic bacteria · Nitrogen fixation · Sustainable agriculture · Biocontrol Abiotic stress tolerance

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M. Hasanuzzaman (ed.), *Agronomic Crops*,
https://doi.org/10.1007/978-981-32-9783-8_17

17.1 Introduction

Useful plant species termed as “crops” are managed in agriculture to obtain products for mankind. On the contrary, plant species named “weeds” are not desirable but are found in agroecosystems. Though weed seed is not sown intentionally by the human, it is well adapted to the environment and grows or reproduces aggressively in association with crops from the beginning of agriculture (Janick 1979; Peterson and Peterson 1999). Weeds take part in yield loss by reducing the potential harvestable crops due to crop-weed competition for uptake of available resources or by reducing actual amount of harvested products due to interference in harvesting and threshing operations (Chandler 1980; Nave and Wax 1971; Bhandari and Sen 1979; Aldrich 1984; Zimdahl 1980). To gain establishment advantages over surrounding crop plants, weeds also produce allelochemicals which inhibit the germination, growth, and development of crop plants (Putnam and Weston 1986; Rice 1986). Again secretion of negative microbial allelopathies by the weeds in the rhizosphere inhibits the development of microorganism including endophytic bacteria which results in the reduction of emergence, withstanding, and growth of desirable crops (Schippers et al. 1987; Sturz and Christie 1996; Barazani and Friedman 1999). In the negative context, weeds are contemplated as interfering associates of desired crops, and their value is judged solely in terms of yield reduction. In agroecosystem, weeds are considered as unwanted intruders that compete for resources with desired crops, force to use more labor and technology to eliminate for better yield (Fickett et al. 2013). However, weeds also play an important role in agroecosystem as genetic resources for food agriculture and pharmaceutics and as indicators of biodiversity (Spahillari et al. 1999). Several lines of evidence suggest that weeds harbor diverse group of endophytic bacteria that exert beneficial effects to their weed host in various ways (Sorty et al. 2016; Samad et al. 2017a, b). Discovery of those interesting bacteria and search for their beneficial usage in crop production have been investigated (Krimi 2016; Lafi et al. 2017).

Due to climate change and other factors, production of food for the increasing population of the world is very challenging. Biotic and abiotic stresses such as drought, high temperature, salinity, etc. are also increasing. Emergence of disease is alarmingly increasing which poses a threat to future food security (Islam et al. 2016). Current synthetic agricultural inputs are very expensive, and application of these inputs seems unable to mitigate emerging challenges. Therefore, the most demanding issue in agriculture and agri-food sector is to achieve eco-friendly and sustainable development by boosting up crop productivity through biorational utilization of limited natural resources (Islam et al. 2017; Rahman et al. 2018). Adoption and management of new biotechnological approaches and crop production strategies can enhance productivity and competitiveness of agriculture (Fahey et al. 1991; Kloepper 1992). Application of endophytic plant growth-promoting bacteria (PGPB) is one of the viable biotechnological approaches toward sustainable agriculture (Turner et al. 1993). Both crop plant and weeds host the highly diverse microbial communities, which strongly interact with their hosts in various ways ranging from symbiosis, mutualism, to commensalism or pathogenic forms (Carroll

1988; Walker 1992; Newton et al. 2010; Hardoim et al. 2015). These interactions contribute to improve soil quality, plant health, and plant productivity by soil organic matter mineralization, stimulation of plant defense mechanisms, and prevention of phytopathogens (Lugtenberg and Kamilova 2009; Compant et al. 2010; Bhattacharyya and Jha 2012; Khatun et al. 2018). Considering the deleterious effects of synthetic agrochemicals to soils, environment, and even human health, application of beneficial endophytic bacteria is considered as a biorational approach for sustainable nutrition and protection of crop plants. Although a large body of literature is available on crop plant-associated PGPB, there is no comprehensive review that has so far been published on discoveries of endophytic bacteria from weeds and their potential usage in sustainable crop production. Therefore, this review attempts to explore the recent discoveries of beneficial endophytic bacteria from various weed species and discusses their effects on different crop species.

17.2 Concept of Endophytes and Their Role on Host Plant

More than 150 years ago, De Bary first coined the term "endophyte" for pathogenic fungi that enter into the tissues of plant leaves (Bary 1866). Since then, this term is redefined by many researchers, but each has its own restrictions. However, the word "endophyte" is derived from two Greek words (endon = within, phyton = plant), which means "in the plant" (Chanway 1996). The bacteria that can be detected at a particular moment within the tissue of apparently healthy plant hosts without inducing disease or organogenesis are known as endophytic bacteria (Chanway 1996). The first occurrence of the plant endophytic bacteria was reported by Trevet and Hollis (1948) in the internal tissues of a healthy potato plant. With the advancement of time, several studies were conducted to isolate the endophytic bacteria from different plants and evaluated their capability as PGPB (Hallmann et al. 1997; Kobayashi and Palumbo 2000; Sturz et al. 2000; Rosenblueth and Martínez-Romero 2006; Suman et al. 2016). Endophytic PGPB have several advantages over free-living, rhizospheric, or phyllospheric probiotic bacteria as endophytes are protected from various abiotic and biotic stresses such as extreme temperature, drought, nutrient, pH, water availability, and competition with other organisms (Loper et al. 1985; Cocking 2003). Besides, these bacteria colonize in the internal tissue and form mutualistic relationships, i.e., plants get fixed N_2 and provide nutrients in return (Richardson 2009; Reinhold-Hurek et al. 1998a, b; Santi et al. 2013). Endophytic bacteria can colonize well in rhizosphere and in variety of plant organs such as roots, leaves, stems, flowers, fruits, and seeds (James et al. 2002; Sessitsch et al. 2002; Berg et al. 2005; Okunishi et al. 2005; Compant et al. 2011; Pereira et al. 2012; Trognitz et al. 2014; Rahman et al. 2018). They can even colonize legume nodules and tubercles of mycorrhizal fungi (Benhizia et al. 2004; Paul et al. 2013). In different plant parts, the population of endophytic bacterial greatly varied from as low as hundreds to as high as billions per gram plant tissue (Jacobs et al. 1985; Misaghi and Donndelinger 1990; Sturz et al. 1997; Chi et al. 2005). Colonization of endophytic bacteria not only enhance growth but also promote quality of the produce of crop plants (Rahman et al. 2018).

Table 17.1 Taxonomic diversity of various beneficial bacteria isolated from weeds

Bacterial genera isolated from weed	Family
Agrobacterium	*Rhizobiaceae*
Arthrobacter	*Micrococcaceae*
Alkaligenes	*Alcaligenaceae*
Bacillus	*Bacillaceae*
Curtobacterium	*Microbacterium*
Caulobacter	*Caulobacteraceae*
Herbaspirillum	*Oxalobacteraceae*
Marinobacterium	*Alteromonadaceae*
Microbacterium	*Microbacteriaceae*
Micrococcus	*Micrococcaceae*
Pseudomonas	*Pseudomonadaceae*
Rhodococcus	*Nocardiaceae*
Sinorhizobium	*Rhizobiaceae*
Sphingonomas	*Sphingomonadaceae*
Stenotrophomonas	*Xanthomonadaceae*

17.3 Taxonomic Diversity of Weed Endophytes

The taxonomic diversity of weed endophytic bacteria are diverse. The endophytes isolated from different organs of weed plant showed significantly different abundances of shared taxa between bacterial species at the family as well (Table 17.1). Reviewing literature indicates that the families *Bacillaceae* and *Pseudomonadaceae* cover most of the endophytic bacteria identified from the weed.

A diverse community of bacterial endophytes was found in weed which helps in promoting plant's growth. Endophytic bacteria from a range of invasive weed, for instance, babchi, white popinac, Johnson grass, Santa-Maria, Thanet cress, nettle leaf, little clock, lambs tongue, sticky snakeroot, split-leaf lettuce, yellow-berried nightshade, wild tobacco, slough grass, and nut grass, not only fix atmospheric nitrogen and solubilize inorganic minerals in soils (such as phosphorus) but also act as biocontrol agent against notorious phytopathogens. Some of these weed endophytic bacteria also enhance stress tolerance to the host plants against drought and salinity (Table 17.2).

17.4 Mechanism of Plant Growth Promotion by Weed Endophytic Bacteria

Commensal endophytes have no apparent effects on plant activities but live on the metabolites produced by the host, whereas other endophytes (PGPB) exert several benefits to the plant such as protect the plants from invading pathogens and herbivores by antibiosis or induced resistance mechanism (Scortichini and Loreti 2007). Generally, in optimum growth condition, bacterial endophytes generally showed neutral effects to the host plant, whereas they confer beneficial effects during

Table 17.2 Name, source of isolation and their beneficial effects of endophytic bacteria isolated from the weed species

Name of the bacterial isolates	Name of the plant species	Plant part	Beneficial traits isolated bacteria	Applied crop species	References
Bacillus sp., *Sinorhizobium* sp., *Marinorhizobium* sp.	*Psoralea corylifolia*	Root nodule	Plant growth promotion under salinity stress condition	Wheat	Sorty et al. (2016)
Rhodococcus kroppenstedtii, Sphingomonas paucimobilis, microbacterium proteolyticum, Sphingomonas paucimobilis, microbacterium proteolyticum, Sphingomonas pseudosanguinis, Pseudomonas oryzihabitans	*Leucaena leucocephala*	Shoot	Degrades mimosine for N-fixation	–	Ulloa et al. (2017)
Xanthomonas melonis, agrobacterium tumefaciens, Sphingobium amiense, Pseudomonas jessenii, Caulobacter vibrioides	*Sorghum halepense*	Roots, rhizosphere	N-fixation	–	Rout and Chrzanowski (2009)
Bacillus sp.	*Parthenium hysterophorus*	Stem, root	Biocontrol agent against downy mildew	Pearl millet	Chandrashekhara (2007)
Pseudomonas viridiflava	*Lepidium draba*	Stem, root	Bicontrol agent	Vineyard	Samad (2017a)
Pseudomonas sp., *Arthrobacter* sp., *Bacillus* sp.	*Lepidium draba*	Root	Produce hydrogen cyanide, phosphate solubilization	Grape vine	Samad (2017b)
Bacillus methylotrophicus, Bacillus pumilus, Bacillus cereus, Bacillus amyloliquefaciens	*Urtica dioica*	Root	Plant growth promotion, biocontrol agent	Tomato	Krimi (2016)
Pseudomonas brassicacearum, Bacillus amyloliquefaciens	*Calendula arvensis*				
Bacillus sp.	*Plantago lanceolata*				

(continued)

Table 17.2 (continued)

Name of the bacterial isolates	Name of the plant species	Plant part	Beneficial traits isolated bacteria	Applied crop species	References
Stenotrophomonas maltophilia, S. rhizophila	*Eupatorium adenophorum*	Vascular tissue of root and stem	Plant growth promotion, bioremediation, production of secondary metabolites	Oil seed rape, sugar beet, wheat, canola, potato, poplar	Ryan et al. (2009)
Pseudomonas mendocina	*Lactuca dissecta*	Root	Plant growth promotion	Corn	Naz and Bano (2010)
Pseudomonas stutzeri	*Solanum surattense*	Root			
Pseudomonas putida	*Sonchus arvensis*	Root			
Bacillus cereus	*Nicotiana glauca*	Stem	Biocontrol		Abdallah et al. (2016)
Alcaligenes faecalis		Leaves	Agent, plant growth promotion	Tomato	
Herbaspirillum frisingense	*Spartina pectinata*	Root, stem, leaves	N- fixation	–	Kirchhof et al. (2001)
Micrococcus luteus	*Cyperus conglomeratus*	Root	Oxidative tolerance, salinity, and stress tolerance	–	Lafi et al. (2017)

various stages of the plant life cycle or under more extreme conditions. However, in case of the fungal endophytes, the fungus *Fusarium verticillioides* has a dual role both as a pathogen and as a beneficial endophyte in maize (Bacon et al. 2008). Not only the host genotype but also the abiotic stresses are responsible for such dual states. Abiotic stresses lessen the host fitness which distort the delicate balance. Disease occurrence and mycotoxin production by the fungus are also responsible for unbalancing the plant condition (Bacon et al. 2008). However, beneficial effects have also been demonstrated, e.g., several strains of *F. verticillioides* protect their host by suppressing the growth of another pathogenic fungus *Ustilago maydis* (Estrada et al. 2012).

17.4.1 Plant Growth Promotion

To date, plant growth-promoting effects attributed to endophytic bacteria have encompassed growth and developmental promotion through the enhanced availability of minerals (Frommel et al. 1993; Kloepper et al. 1980, 1991; Davison 1988; Murty and Ladha 1988), growth inhibition of pathogenic organisms (Fredrickson and Elliott 1985; Schippers et al. 1990), growth stimulation indirectly through the biocontrol of phytopathogens in the root zone, induction of phytohormone synthesis by the plant (Bakker and Schippers 1987; DéFago et al. 1990; Lazarovits and Nowak 1997), and the direct production of phytohormones (Barbieri et al. 1986; Brown 1974; Jacobson et al. 1994; Tien et al. 1979; Holland 1997; Rahman et al. 2018), altered susceptibility to frost damage (Gagné et al. 1989; Xu et al. 1998), and altered plant susceptibility to other pathogens (Fredrickson and Elliott 1985; Schippers et al. 1990).

17.4.2 Nitrogen Fixation

The major sources of nitrogen for agricultural soils are from mineral fertilizers and biological nitrogen fixation (Chanway et al. 2014). Due to the intensification of agriculture, contamination of ground and surface water by chemical fertilizers and coliform bacteria has emerged as significant human health and environmental issues (Anon 1997a, b). In case of green agriculture, while intensifying the use of legumes may serve to elevate N levels in root residues and form a source for subsequent crops. The N from root residues and easily mineralized soil organic matter will also form a source of leached N. Thus, nitrogen loss in green manuring systems can be equivalent to that from fertilizer nitrogen (Harris et al. 1994; Addiscott et al. 1991). By contrast, fertilizer inputs are expensive and nonrenewable, and excess nitrogen may lead to the production of N_2O, a “greenhouse gas.” One viable approach for improving the nitrogen economy of crops can be the application of N-fixing endophytic bacteria to nonleguminous crops in rotations that they would fix atmospheric nitrogen for enhanced crop production (Sloger and Van Berkum 1992). Rout and Chrzanowski (2009) demonstrated that *Xanthomonas melonis*, *Agrobacterium* *tumefaciens*, *Sphingobium amiense*, *Pseudomonas jessenii*, and *Caulobacter vibrioides* isolated from the root and leaves of invasive plant species *Sorghum halepense* fix nitrogen through nitogenase activity. Rangel et al. (2016) found that *Rhodococcus kroppenstedtii*, *Sphingomonas paucimobilis*, *Microbacterium proteolyticum*, *S. pseudosanguinis*, and *Pseudomonas oryzihabitans* isolated from *Leucaena leucocephala* enzymatically break down mimosine into the intermediate 3-hydroxy-4-pyridone (HP) and use it as a carbon/nitrogen source where mimosine is antagonistic to a variety of plants and weeds.

17.4.3 Phosphorus Solubilization

Plant-associated bacteria solubilize insoluble phosphate complexes by releasing organic acids and form orthophosphate which is available for plant uptake and utilization. In return bacteria use root carbon mainly sugar and organic acids to maintain their life. Samad et al. (2017a, b) demonstrated that endophytic bacteria *Arthrobacter* sp., *Bacillus* sp., and *Pseudomonas* sp. isolated from *Lepidium draba* confer the ability to solubilize inorganic phosphate and make it available to the plant. *Bacillus cereus* and *Alcaligenes faecalis* isolated from *Nicotiana glauca* solubilize phosphate and make it available to the tomato plant (Abdallah et al. 2016). *Pseudomonas mendocina*, *P. stutzeri*, and *P. putida* isolated from *Lactuca dissecta*, *Solanum surattense*, and *Sonchus arvensis*, respectively, solubilize phosphate through the production of organic acids in saline soil (Naz and Bano 2010).

17.4.4 Indole Acetic Acid Production

Indole-3-acetic acid (IAA), a physiologically active auxin, is crucial for plant growth and development. It is responsible for longer root production, increasing the number of root hairs which is involved in nutrient uptake in the plants. The IAA is synthesized in L-tryptophan metabolism and produced by several microorganisms including plant endophytic bacteria (Datta and Basu 2000). Besides, IAA acts as a principle agent in controlling plant responses in case of environmental changes (Tuteja 2007; Malhotra and Srivastava 2009). *Bacillus* sp., *Sinorhizobium* sp., and *Marinobacterium* sp. isolated from the root nodule of *Psoralea corylifolia* produce IAA which enhances the germination and establishment of wheat by interacting with abscisic acid, gibberellins, and ethylene-mediated pathways under saline stress condition (Sorty et al. 2016). Samad et al. demonstrated that *Pseudomonas* sp. isolated from *Lepidium draba* produces IAA and exhibits great impact in grape vine. *Pseudomonas mendocina*, *P. stutzeri*, and *P. putida* isolated from *Lactuca dissecta*, *Solanum surattense*, and *Sonchus arvensis* produce IAA in *Zea mays* (Naz and Bano 2010). Recently, Abdallah et al. (2016) demonstrated that *Bacillus cereus and Alcaligenes faecalis* produce IAA which induces plant growth promotion.

17.4.5 Protection against Biotic and Abiotic Stresses

Endophytic bacteria occupy a great role in plants defense systems (Islam et al. 2005; Khatun et al. 2018). They evolve in the plants at a faster rate because of their short life span than the host and develop higher selection of antagonistic form. This phenomenon increases the resistance of plants against short-living pathogens and herbivores. Endophytic bacteria protect plants from pathogenic microoraginsm through production of antimicrobial compounds (Islam et al. 2005; Islam and von Tiedemann 2011) and ISR in host plants (Carroll 1991).

Endophytes induces systemic resistance (ISR), that leads to a higher tolerance of pathogens (Seilaniantz et al. 2011; Zamioudis and Pieterse 2012). At the very beginning of colonization of bacteria, the plants exert immune defense similar to pathogen. But the endophytic bacteria escape and colonize to the plants (Zamioudis, Pieterse 2012). *Pseudomonas* and *Bacillus* are two important genera of bacteria that generally exert ISR (Chanway 1998; Kloepper and Ryu 2006), although ISR induction is not exclusive to these groups (Ardanov et al. 2011; Bordiec et al. 2011). Bacterial factors responsible for ISR induction were identified which include flagella, antibiotics, *N*-acylhomoserine lactones, salicylic acid, jasmonic acid, siderophores, volatiles (e.g., acetoin), and lipopolysaccharides (Bordiec et al. 2011; Loon et al. 2008). On the other hand, *A. faecalis* S18 and *B. cereus* inhibited mycelial growth of pathogen and formed an inhibition zone via production of lytic enzymes such as chitinases and/or proteases among other substances. In fact, synthesis of lytic enzymes, such as chitinase, protease, and *β*-1,3-glucanase, is involved in cell wall degradation during antagonism (Abdallah et al. 2016). *Pseudomonas viridiflava* is a pectinolytic bacterium isolated from the weed *Lepidium draba* L., which showed inhibiting effects toward its host. *Bacillus pumilus* isolated from *Urtica dioica* and *B. methylotrophicus* isolated from *Plantago lanceolata* are the most effective against pathogenic agrobacteria strains. Two bacterial strains of *Bacillus* spp. isolated from *Euphorbia helioscopia* and *Plantago lanceolata* are most efficient in control of *Pectobacterium* spp. (Krimi et al. 2016). The potentiality of *Stenotrophomona*s spp. for the biocontrol of plant pathogens has been documented in several systems such as monocot and dicot crops as hosts. *S. maltophilia* strains have a remarkable high hydrolytic potential. They produce various enzymes such as proteases, DNases, chitinases, glucanases, RNases, lipases, and laccases (Berg et al. 1996; Galai et al. 2008; Islam 2011). Both chitinolytic and proteolytic activities of *S. maltophilia* contribute to the biocontrol activity (Zhang and Yuen. 1999, 2000a, b; Zhang et al. 2001). Chitinases might protect plants against fungal pathogens through fungal cell wall lysis but might also have a role in triggering plant defense mechanisms (Mastretta et al. 2006). A chitinase from *S. maltophilia* strain C5 was shown to suppress summer patch disease (caused by *Magnaporthe poae* Lanschoot and Jackson) in Kentucky bluegrass by the activation of disease resistance genes (Kobayashi 2002). *Bacillus* spp. isolated from *Parthenium hysterophorus* inhibit downy mildew of pearl millet by producing antimicrobial compound (Chandrashekhara et al. 2007).

Several abiotic stresses such as high temperature, salinity, and moisture deficiency etc. affect the the growth of crop plants and so forth, these stresses also affect the microbes. Plant growth-promoting endophytic bacteria (PGPB) have been identified as a group of microbes that are used for plant growth enhancement and biocontrol for management of plant diseases. The PGPB which showed beneficial effect in the laboratory can't withstand in the field due to the prevailing abiotic stresses. Therefore, for obtaining the benefits of PGPB at the field level, abiotic stress tolerance bacterial strains should be selected (Kumar et al. 2014). Lafi et al. (2017) found *Micrococcus luteus* isolated from *Cyperus conglomeratus* shows salinity and oxidative stress tolerance under salt-stress conditions. Another study showed that *Pseudomonas viridiflava* isolated from *Lepidium draba* confered metal and herbicide resistance in vineyard. *Stenotrophomonas* spp. are promising candidates for biotechnological applications in agriculture. Many *S. maltophilia* strains carried intrinsic resistance to various heavy metals. For example, the *S. maltophilia* strains Sm777 and D457R showed tolerance to various toxic heavy metals, such as mercury, cobalt, cadmium, zinc, lead, and silver (Alonso et al. 2000). When tested in tenfold diluted tryptic soy broth, strain Sm777 is additionally tolerant to 50 mM selenite, 25 mM tellurite, and 50 mM uranyl salts. These properties of *S. maltophilia* have the potential to be exploited for bioremediation purposes or to aid phytoremediation. Furthermore, *S. maltophilia* strains could be useful in the bioremediation of heavy metal polluted soils and xenobiotics. *S. maltophilia* strains also produce bioactive compounds, including antibiotics and enzymes (Pages et al. 2008; Cao et al. 2009; Siegert et al. 2007).

17.5 Concluding Remarks

A fuller understanding of the versatility, adaptation, and potential uses of the fascinating weed associated endophytic bacteria opens up a new way of utilizing them in sustainable agroculture. Global climate change is posing serious threat to crop production through increasing various biotic and abiotic stresses to crop plants. The PGPB isolated from the weeds can be also applied under stress condition to mitigate biotic and abiotic stressed as well as to supplement chemical fertilizer or pesticides for obtaining sustainable crop production. This study represents a good starting point to think and research with weed as a major component of agroecosystem and potential sources of novel endophytic bacteria. Investigation of the molecular understanding of the weed-bacterial interactions would be very interesting for further exploitation of these potential novel biologics in the nutrient management of crops growing under stressful conditions. To further understand the highly complex nature of the microbial adaptation and response to the alterated biological, chemical, and physical environment of the plant remains a significant challenge. Developing an efficient and longer shelf-life of the PGPB formulation as well as biocontrol agent is a time-demanding approach for their wider use in sustainable agriculture. Recent advances in genomic and post-genomic analytic approaches would help to understand underlying molecular mechanisms of the beneficial effects of weed endophytes and utilize them as a biorational tools for the mitigation of some challenges in crop production due to global climate change.

Acknowledgments The authors are thankful to the Ministry of Science and Technology of the Government of Bangladesh, RMC of BSMRAU, World Bank, and Bangladesh Academy of Sciences for partial funding of this work.

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