DOI: 10.34101/ACTAAGRAR/1/12043

Seed treatment with *Bacillus* bacteria improves maize production: a narrative review

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SUMMARY

Maize (Zea mays L.) is an important crop in relation to its production and consumption. Production of maize is constrained by soil infertility and poor quality seed. Microbial technologies like seed treatment with Bacillus bacteria improves the productivity of maize on infertile soil. However, due to variations in maize growth environments and Bacillus species, this review was conducted to identify the common species of Bacillus species used for seed treatment, and provide an overview of the effect of seed treatment with Bacillus on maize growth and yield. Results show that Bacillus subtilis, Bacillus pumilus and Bacillus amyloliquefaciens were the dominant species used for seed treatment. Bacillus was used as both a biofertiliser and biopesticide. The conspicuous positive effects of Bacillus were in plant height, shoot and root length, and shoot dry matter depending on the species. In terms of grain yield, Bacillus subtilis (8502 kg ha^{-1}), Bacillus amyloliquefaciens (6822 kg ha^{-1}) and Bacillus safensis (5562 kg ha^{-1}) were the bacterial species that had an overall pronounced effect. The highest increase in grain yield was in the interactive effect of Bacillus megaterium + Bacillus licheniformis (18.1%) and sole Bacillus subtilis (15.6%), while Bacillus pumilus reduced grain yield by 4.8%. This shows that the improvement of maize productivity using Bacillus bacteria requires careful selection of the species for seed treatment.

Keywords: *Bacillus bacteria; biopriming; maize; seed treatment; yield*

INTRODUCTION

Maize (*Zea mays* L.) is a cereal crop of economic and social significance contributing two thirds of human energy consumption globally (Mumtaz et al., 2017; Xue et al., 2019; Jalal et al., 2022); as such necessitates increased production to meet significantly increasing human population (Szeles et al., 2012; FAO, 2020; Illés et al., 2020; Ferrarezi et al., 2022). The ability of maize to sustain global human nutrition is hampered by nutrient deficiency, hidden hunger, deteriorating soil fertility (Bojtor et al., 2022; Jalal et al., 2022), and extreme climatic conditions (Tesfaye et al., 2017; Notununu et al., 2022). Mitigating adverse effects of abiotic stresses requires practices that increase nutrient use efficiency at the same time addressing ecological trepidations (Karthika et al., 2013; Shaffique et al., 2022; Zakavi et al., 2022). Besides this, the challenge of low quality seed affects productivity of crops including maize since it affects stand establishment (Rashid et al., 2002), exacerbated by environmental stresses resulting into patchy crop stands and decreased yield (Harris et al., 2001; Meena et al., 2013; Chatterjee et al., 2018). Hence, the urgent implementation of seed enhancement technologies starting from sowing will acts as an impetus to proper crop establishment (Sarkar et al., 2021) and later improve nutrient utilization by crops (Pereira et al., 2020).

Seed treatments (inoculation and/or biopriming) with plant growth-promoting bacteria (PGPB) such as *Azospirillum*, *Bacillus* and *Pseudomonas* characterize a sustainable approach to increase maize productivity (Zeffa et al., 2019; Pereira et al., 2020; Pfeiffer, et al., 2021; Li et al., 2021; Katsenios et al., 2022). The bacteria produces growth promoting phytohormones, (Fukami et al., 2017), solubilizes phosphates (Luduena et al., 2018; Qi et al., 2018), improves biological nitrogen fixation and nutrient availability (Hayat et al., 2010; Ji et al., 2014; Pankievicz et al., 2015; Galindo et al., 2018) and can be used in pathogen control (Cavaglieri et al., 2005; Disi et al., 2018). Therefore, the multi-functional nature of the bacteria and its application methods determines the nature of impact depending on the agroecosystem (Babalola, 2010; Berg et al., 2014; Bhattacharyya and Jha, 2012; Naamala and Smith, 2020; Mitter et al., 2021).

The bacteria genera, *Bacillus* are reported to show a pronounced plant growth promotion capability (Wang et al., 2009; Lima et al., 2011; Gond et al., 2015; Akhtar et al., 2016; Abadi et al., 2020) as well as antimicrobial compound production (Stein et al., 2005). For this reason, attention has been shifted to seed biopriming with *Bacillus*. Biopriming improves stand establishment (Shaffique et al., 2022) and tolerance to environmental stresses (Mahmood et al., 2016; Sandini et al., 2019; Piri et al., 2019; Roslan et al., 2020; Singh et al., 2020; Negi and Bharat, 2021). Environmental stress is ameliorated through accumulating polyphenols and flavonoids (secondary metabolites) and organic molecules (polyamines, proline) which act as stress defense mechanisms (Singh et al., 2020; Sarkar and Rakshit, 2020). Accordingly, seed biopriming makes integrated nutrient management more effective (Devika et al., 2021). Additionally, biopriming is cost friendly and reduces interference with biological equilibrium (Rajendra et al., 2016; Sarkar et al., 2021).

DOI: 10.34101/ACTAAGRAR/1/12043

Diverse published literature shows mixed effects (positive and/or negative or null effect) of biopriming or inoculating maize seeds with several *Bacillus* species. In fact, Rocha et al. (2019) noted that not entirely published literature indicates the positive effects of *Bacillus* seed treatment on crop performance. For example, *Bacillus subtilis* lipopeptides extracts offer defence against *Fusarium moniliforme* by inducing pathogenesis related genes (Gond et al., 2015). According to Li et al. (2021), seed biopriming with *Bacillus* species B-MGW9 improved germination by reducing salt stress deleterious effects. On the contrary, Pereira et al. (2011) indicated that germination was not affected by inoculation with *Bacillus amyloliquefaciens.* According to Mubeen et al. (2021), effects of the *Bacillus* species on growth parameters have a pronounced effect on the final yield. Based on this contradicting literature, this review was conducted to provide all-inclusive overview of the effect of different Bacillus bacteria species on the growth and yield performance of maize.

METHODOLOGY

This review adopted a narrative approach where literature was searched from different databases; Web of science (WoS), Scopus and Google scholar. Literature from articles that clearly provided the effects and/or direction of effect of *Bacillus* bacteria on maize growth and yield was considered. The relevant literature was reviewed, synthesized, and summarized.

RESULTS AND DISCUSSION

Effect of seed treatment with *Bacillus* bacteria on selected growth parameters of maize

Abiotic and biotic stresses affect growth of maize by disrupting key metabolic processes. However, some biotic agents like bacteria interact synergistically with maize plants. Bacteria can be used as a biofertiliser and/or biopesticides to replace synthetic fertilisers and pesticides (Hashem et al., 2019) that have a negative impact on human and environmental health in along run. Application of different *Bacillus* species inform of seed treatment as biofertilisers or biopesticides elicits varying results. For example, sample, Cano Camacho et al. (2023) reported that treatment of seeds with *Bacillus thuringiensis* EX297512 + *Bacillus firmus* I-1582 had diminutive effect on plant height, lodging and NDVI. Similarly, Vagedes and Lindsey (2020) revealed that root porosity of maize hybrid wasn't affected by *Bacillus firmus* I-1582 seed treatment. Accordingly, *Bacillus firmus* I-1582 as a nematicide for control of Meloidogyne incognita race 3 root-knot nematode did not significantly affect seedling fresh weight (Hagan et al., 2015). Correspondingly, *Bacillus pantothenticus* decreased aboveground fresh biomass of maize compared with the control (Amogou et al., 2019). The complex interactions between the *Bacillus* species and the components of the agroecosystems could partly explain the failure of the bacteria to elicit the desired effects.

Contrary to the above, some literature reports a positive and significant effect of *Bacillus* bacteria on some maize growth parameters. For example, *Bacillus subtilis* formulation as a biopesticide improved plant height by 9.5% reflecting the ability of this bacteria to trigger plant growth (Djaenuddin et al., 2021). Additionally, Djaenuddin et al. (2021) discovered that corn plants treated with *Bacillus subtilis* biopesticide increased leaf chlorophyll content resulting into improved photosynthesis. Meanwhile, Houida et al. (2022) showed that seeds bioprimed with *Bacillus subtilis* isolated chloragogenous tissue of the earthworm significantly improved the germination, root elongation (from 67% to 84%) and biomass. According to Vagedes and Lindsey (2020), seed treatment with *Bacillus firmus* I-1582 positively influenced root surface area and plant height. Moreno et al. (2021) noted seed inoculation with *Bacillus subtilis* increased stem diameter and nitrogen content in maize plants. Also, Accinelli et al. (2017) revealed improved shoot (8.4%) and root length (and 8.7%) of seedlings from *Bacillus subtilis* coated corn seeds. The improvement of the growth parameters was because *Bacillus subtilis* solubilized phosphate and potassium, produced the phytohormone indole-3-acetic acid (IAA) and nitrogen which played vital roles in plant physiological processes. Besides, other species like *Bacillus toyonensis* strain Bt04 promoted maize root development and growth by increasing auxin efflux as well as improved resistance of roots to aluminium toxicity (Zerrouk et al., 2020). Similarly, Jalal et al. (2022) reported seed inoculation with *Bacillus subtilis* increased maize shoot dry matter by average of 3.3% in two seasons under residual zinc fertilisation. This shows that *Bacillus subtilis* has the ability to increase zinc utilization efficiency in maize plants. On the other hand, biopriming of seeds with *Bacillus* B-MGW9 improved the length of the lateral root, seedling shoot fresh and weight, as well as seedling root fresh and dry weight (Li et al., 2021) by exhibiting characteristics of salt tolerance, phosphorus dissolution, nitrogen fixation, and IAA production. The stimulative effect of Indole-3-acetic acid provides benefit to early maturing maize genotypes to overcome unfavourable weather conditions at the initial phenophases (Dordevic et al., 2017). Early establishment of maize plants ensures their ability to yield under subsequent environmental stresses. According to Rudolph et al. (2015), *Bacillus cereus* enhances the early development and growth maize. According to Cardarelli et al. (2022), the overall physiological and phenological impacts elicited on maize depends on the *Bacillus* spp. In addition, our synthesis shows that the effect of *Bacillus* species on maize growth varied by nature of abiotic and biotic factor ameliorated.

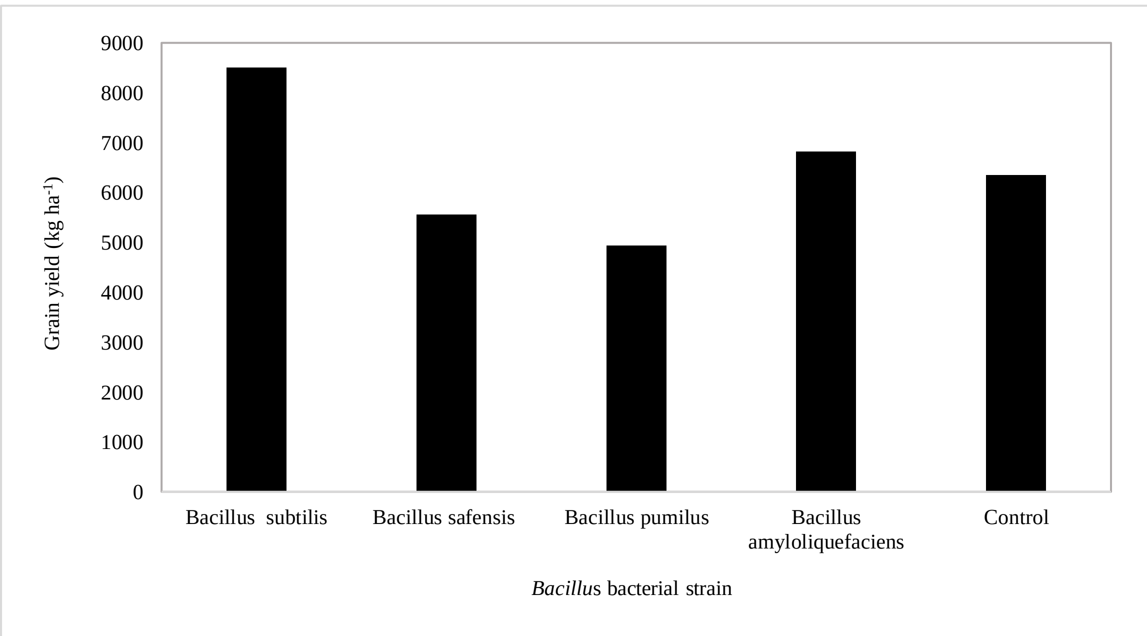
Effect of seed treatment with *Bacillus* bacteria on maize yield

The grain yield response to *Bacillus* species was examined by various authors with the key species being *Bacillus subtilis safensis, Bacillus amyloliquefaciens* and *Bacillus pumilus*. A study by Cano Camacho et al.

DOI: 10.34101/ACTAAGRAR/1/12043

(2023) revealed that *Bacillus thuringiensis* EX297512 + *Bacillus firmus* I-1582 in combination with fungicide improved yield by 1500 kg ha^{-1} compared to the control. According to Breedt et al. (2017), *Bacillus safensis* had pronounced yield increase in light infertile soil compared to heavy fertile soil; implying that yield varied by soil type. The combination of *Bacillus safensis, Bacillus pumilus* and *Lysinibacillus sphearicus* had slightly lower yield compared to sole application reflecting additive effect. Accordingly, Pereira et al. (2010) reported that *Bacillus amyloliquefaciens* increased grain yield by 9.3%. Similarly, Hagan et al. (2015) shows that the grain yield from Clothianidin + *Bacillus* firmus differed significantly from thiamethoxam, Abamectin + thiamethoxam, except Clothianidin. According to Egamberdiyeva (2007), inoculation compensates for deficiency of nutrients consequently improving plant development through production of growth regulators by microbes at the root interface, which stimulate root development resulting into better absorption of water, and nutrients from the soil. A study by Jalal et al. (2022) shows that inoculation with *Bacillus subtilis* increased 100 grains weight by 8.1% compared to control. Additionally, height of insertion of first productive cob and overall grain yield of maize increased under residual Zn fertilisation. Therefore, "*Bacillus subtilis as an efficient alternative to improve Zn acquisition and use efficiencies and consequently maize productivity though co-inoculation under different soil conditions in the field was recommended"* (Jalal et al., 2022). Similarly, Pereira et al. (2020) revealed inoculation with *Bacillus subtilis* increased P uptake and use efficiency that improved development of productive yield components and improvement of grain yield by 15.9%. However, the study recommended further investigations of *Bacillus subtilis* effect on maize under attack pathogens and insects, drought, salinity, among other stresses when inoculated as sole or in co-inoculated. Generally, the improvement of yield by *Bacillus subtilis* depends on the maize variety, soil type and inoculation method (Djaenuddin et al., 2021). The positive effect of *Bacillus* on grain yield is partly because inoculation of maize seeds improves the soil fertility by increasing available nitrogen soil content (Mandić et al., 2018). This saves the amount of nitrogen fertiliser for subsequent crop in rotation. Likewise, Inoculation of maize seeds with *B. amyloliquefaciens* isolate 1 increased maize yield by reducing *F. verticillioides* infection during the two years of the experiment (Pereira et al., 2010). Overall, our synthesis from selected articles shows that the highest and lowest grain yield were recorded in *Bacillus subtilis* and *Bacillus pumilus* respectively (*Figure 1*). Looking at the direction of yield change, *Bacillus subtilis*, *Bacillus amyloliquefaciens, Bacillus safensis,* and *Bacillus megaterium* + *Bacillus licheniformis* increased grain yield while *Bacillus pumilus* reduced grain yield by 4.8% (*Figure 2*).

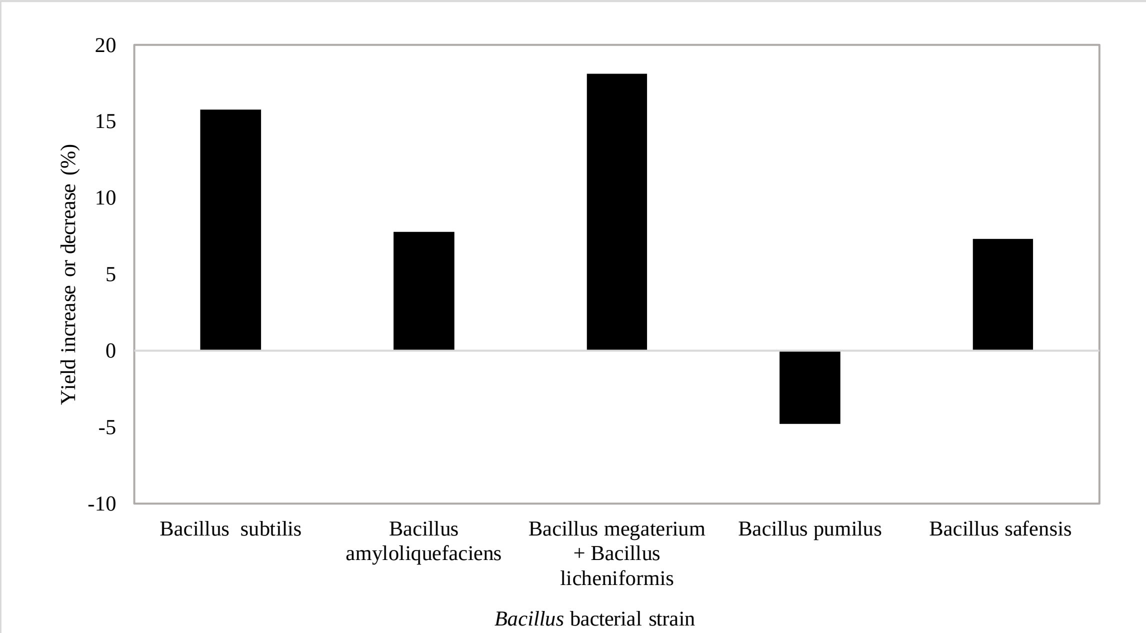
Figure 1. **Effect of *Bacillus* bacterial strains on grain yield**



Aggregated means in the figure are from Houida et al. (2022), Pereira et al. (2010), Mandić et al. (2018), Breedt et al. (2017)

DOI: 10.34101/ACTAAGRAR/1/12043

Figure 2. **Change on grain yield as affected by *Bacillus* bacterial strains**



Percentages in the figure were calculated from data extracted from Breedt et al. (2017), Houida et al. (2022), Mandić et al. (2018), Jalal et al. (2022).

CONCLUSIONS

This review was conducted to provide a narrative overview of the common species of *Bacillus* bacteria used for seed treatment maize seeds and assess their associated effects on maize growth and yield. *Bacillus* bacteria was utilised as both a biofertiliser and biopesticide. *Bacillus subtilis, Bacillus pumilus and Bacillus amyloliquefaciens* were the dominant species used for seed biopriming. The conspicuous positive effects of *Bacillus* were in plant height, shoot and root length, and shoot dry matter depending on the species. In terms of grain yield, *Bacillus subtilis* (8502 kg ha^{-1}), *Bacillus amyloliquefaciens* (6822 kg ha^{-1}), *and Bacillus safensis* (5562 kg ha^{-1}) were the bacterial species that had an overall pronounced effect. The highest increase in grain yield was in the interactive effect of *Bacillus megaterium + Bacillus licheniformis* (18.1%) and sole *Bacillus subtilis* (15.6%), while *Bacillus pumilus* reduced grain yield by 4.8%. This shows that the improvement of maize productivity using *Bacillus* bacteria requires careful selection of the species for seed treatment.

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