Mycorrhizae for Climate Smart Sustainable Agriculture

Somdatta Ghosh, Som Subhra Dutta, Suvashree Bhaumik, Debashis Kuila

To reduce global warming and climate change, a serious threat to agricultural production, we urgently need to reduce the global footprint, specially, the huge portion generated through agricultural practice. To adopt a climate smart agricultural practice, mycorrhizae may be an effective cost-effective tool. Mycorrhizae saves nutrient and water need in soil, offer biocontrol and sequester CO_2 and nitrous oxide. Thus, long-term practice may offer a climate smart agriculture.

Keywords: *Global warming, Climate change, Smart agriculture, Nitrous oxide, Chemical fertilizer*

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Introduction

Around 2050, the global human population would be 9.9 billion, exerting immense pressure on the earth's sustainability, specially, in the area of food and fodder production, waste management and global ecological footprint. The elimination and conversion of agricultural lands is inevitable but the global food demand may be almost double; hence agricultural production must increase to meet the demand (Myers et al., 2017). But increasing global warming and season disruptions are other obstacles to reach the goal in spite the modern breeding programs for crop improvement. Hence, it is urgent to think and step synecologically for a more sustainable system to reduce carbon footprint (CFP), global warming and rise agricultural production with maintenance of soil sustainability. The major percentage of CFP of cereal crop field come from nitrogen fertiliser, then electricity consumption for irrigation, fuel consumption by agricultural machinery and from straw burning (Zhang et al., 2017). The share of the greenhouse gas (GHG) emissions directly related to the production, distribution, use and fate of fertilizers. When evaluating the CFP of fertilizers and pesticides, it is important to assess the complete life-cycle emissions in order to account for all additional sources of GHG emissions beyond the production step. Production of agrochemicals in agriculture demands high energy and water consumption and by produce large quantity of polluted water. The nitrogen mainly leads to N_2O emissions via different pathways. Additionally, most of the N fertilizers acidifies the soil, which is usually compensated by application of lime releasing CO_2 after soil conversion. The fertilizer plants have long term impact on soil, air, water and biodiversity of surroundings. Application of those in fields also hampers soil, biodiversity of land and water through runoff. All these factors add to both carbon and ecological footprints. The most of those pesticides are carcinogenic and with long half-life. To mitigate these negative impacts of CFP, the world is moving towards circular of climate smart agriculture (CSA). Climate-smart agriculture approaches the connected challenges of food security and climate change reducing carbon footprint. CSA propose climate change mitigation and planning for sustainable agricultural systems. The major objectives are- rising in agricultural productivity and farmer incomes, and reducing agricultural greenhouse gas emissions (Deepika et al., 2023). According to Gaia hypotheses, microbes have modified the soil as productive. In nature, plants, rely on microbes only for nutrient supply, not on synthetic fertilizers. Our conventional agriculture is overloaded with synthetic inputs, destroying the soil and microbial harmony. The recent concepts of no input /natural/circular/CSA practices aim to recover and maintain soil sustainability, ensure safe food and minimize carbon footprint. Biotic inputs are integral component of CSA. Soil microbiota composed of bacteria, fungi, archaea etc. co-evolved with plants, among which some are highly beneficial and form some relationships with plants helping them in nutrient uptake, growth regulation, cope to biotic and abiotic stress. Microbes are also responsible for release of N_2O from organic carbon source during decomposition, but the complex interrelationship within microbes is able to lessen the release. Arbuscular mycorrhizae (AM) are the earliest symbiotic association of land plants proving nutrients to sustain, and most abundant symbionts in both natural and agricultural lands and contribution to sustainable agriculture beyond doubt. Beside acting as a substitute of chemical fertilizer, AM is also significant in soil fertility improvement (Liu et al., 2016), playing an essential role in the soil's physical, chemical, and biological components. They increase soil water holding capacity by improving soil structure and enzymatic activity activating other soil microorganisms such as nitrogen-fixing bacteria and phosphate solubilizing microbes (Sadhana et al., 2014). AM also participate in the nitrogen, phosphorus, and carbon cycles while correcting soil acidity (Parihar et al., 2020). AM also provide bio-protection to plant reducing need of synthetic pesticides. AM has direct role in carbon sequestration and reducing greenhouse gases in agriculture.

Mycorrhizae reduces necessity of application of chemical fertilizer

Production and transport of chemical fertilizers demands a lot of energy and water. A large portion of applied fertilizer in soil become unavailable to plants for conversion of forms, leaching, runoff and vitalizations and lost in hydrosphere, atmosphere or pedosphere, merely increasing wastage, expenditure and ultimately the footprint. Arbuscular mycorrhizal fungi (AMF) have been found to increase the growth, biomass and yield of various agricultural crops in a sustainable way (Kumar et al., 2020). AMF acts as a substitute of phosphate (P) fertilizer (Battini et al., 2017), and nitrogen fertilizers also to some degree (Wang et al., 2018); and able to uptake less mobile trace nutrients, particularly in nutrient deficient low P soil. AM efficiently trap P, which is the most conversion and leaching prone mineral and of limited source on earth. AM reduce the need P fertilization due to increased and efficient P uptake. In subsoils, AM increase water-holding capacity, reducing the risk of leaching. AM take up N preferentially in the form of ammonium (NH_4^+), reducing the N pool available for nitrification and check leaching of dissolved nitrate. Though AM inoculations in normal agricultural practice are still limited, it is evident that AM reduces fertilizer demand use up to 50% without compromising the yield (Trezo et al., 2021). AM inoculation also improve crop/ fruit quality, with more nutrient concentration particularly N, P, and Cu, antioxidant compounds, and carotenoid contents in different cereals, vegetables and fruits (Hart et al., 2015; Torres et al., 2018), and aromatic herbs (Zayova et al., 2018). Beside working as substitute of chemical fertilizer alone AM form a consortium with other beneficial soil microbes by interdependence. Mycorrhizae alter the plant secreted strigolactones and other root exudates, induce production of metabolites such as organic acids, volatile and non-volatile compounds to attract a group of micro-flora and can stimulate microbial growth and function in soil (Giovannini et al., 2020). These attracted microbes are mostly plant-growth-promoting microbes (PGPM), belong to species of *Azotobacter, Azospirillum, Flavobacteria, Klebsiella, Chrysebacterium*, *Enterobacter*, *Arthrobacter, Pseudomonas, Actinomyceota, Bacillus* and *Streptomyces* (Battini et al., 2017). These PGPMs assist AM by soil weathering, phosphate solubilization, N fixation, secrete plant growth promoting substances and other volatile compounds and promote both plant and AM fungal growth. These micro-organisms also assist mycorrhiza to colonize with plants under abiotic stressed environment. Thus, the AM and PGPMs are interdependent and mutually enhance functions and population of each other resulting ultimately boosting productivity of agricultural crops. AM maintain the activity of N fixation by retaining the moisture in soil with enmeshing arrangement of fungal mycelia, and further improve water uptake in plant and control stomatal conductance (Augé et al., 2015). Thus, also reduce water related footprint. Some of these rhizospheric microbes including N- fixers and phosphate solubilisers, which enhance the root colonization of AM fungi, known as mycorrhiza helper organism (MHO). All these microbes cooperate each other and create a mycorrhizosphere combination. Thus, AM form a complete sustainable climate smart soil condition in long-term reducing the need of fertilizer.

Mycorrhizae may be and effective biocontrol reducing need of antipathogenic-chemicals

Plant diseases is another major cause to challenge global yield, and cause a 30% yield loss throughout the world. Yet the application of chemical pesticides had been increased significantly in last several decades with acceptance of high yielding crops. Use of chemical pesticides has adverse effect on our health, soil microbes and environment sustainability. Hence the modern world is turning towards the biological or integrated control-based agriculture. Rhizosphere shelters lots of microbes both beneficial and harmful, some are antagonistic to each other, and prior inoculation of plants with the beneficial microbes induce plant defense system also. crops inoculation with AMF is effective to lessen disease severity of soil and air borne pathogens. The long history of several past decades shows the record of AM preventing different diseases caused by fungi, bacteria, viruses and nematodes in different plants in different areas worldwide. AM was found effective against *Sclerotium rolfsi* and *Meloidogyne incognita, Pratylenchus brachyurus, Alternaria*, *Fusarium*, *Colletotrichum*, *Phytophthora* and *Verticillium, Xanthomonas*, *Pseudomonas* spp. and Sardinia virus, Tobacco mosaic virus and Cucumber green mottle mosaic virus, Potato virus Y etc. of different crops. Mycorrhizae provide a Mycorrhiza induced resistance (MIR) induced by a direct plant response against AM colonization too and an indirect response against rhizobacteria, which inhabit in the mycorrhizosphere. As AM is also a biotroph and possesses similarity of other microbial proteins of pathogens, Plant treats them as enemy first and inhibit, but as well as acquires an immunity too against such other pathogens. Microbe associated molecular patterns (MAMP) are accepted by the receptors attached to plant cell surface, known as pattern recognition receptors (PRRs) and induce a set of immunity responses such as MAMP triggered immunity. These reactions include- rapid calcium influx, reactive oxygen species (ROS) accumulation or oxidative burst, phosphorylation reactions, alteration of cell wall, and expression of defense related genes (de Lorenzo et al., 2018). With time AM suppress MAMP triggered immunity (MTI) to colonize in root, but Systemic acquired resistance (SAR) develops keeping MAMPs in memory and quick recognition, action and long-lasting resistance to secondary infection even in the uninoculated arial plant parts also. MIR provides a mode of systemic acquired resistance (SAR) which occur after pathogen infection in plants and induced systemic resistance (ISR) occur following root colonization by non-pathogenic rhizobacteria. The Jasminic acid-dependent defense priming during MIR occur as a result of ISR elicited by rhizobacteria (Dey & Ghosh, 2022). The formation of 'mycorrhizosphere' by AMF invites the beneficial microbes, which triggers plant immunity system by induced systemic resistance (ISR). These microbes in a consortium increase rhizospheric health by interdependency and form suppressive soil for pathogens. MIR can also be successfully established in field conditions (Pérez-de-Luque et al., 2017).

Role of mycorrhiza in carbon sequestration

Carbon dioxide (CO_2) is one of the main greenhouse gases in the Earth's and directly responsible for climate change and global warming. Soil serves as the largest reservoir of carbon in Earths ecosystem holding approximately 1500 gigatons (GT) of carbon in the form of soil organic carbon (SOC) which is nearly double the amount present in the atmosphere (Weissert et al., 2016). The SOC functions as a reservoir of nutrients for both plants and soil microbiome and plays a vital role in regulating global carbon cycle, climate change and serves as a primary indicator of soil health (Hu et al., 2024). Trapping the gaseous C in form of soil C or C sequestration is effective mean to reduce global warming. This SOC stock is primarily determined by the net primary productivity and the allocation of photosynthates between plants and belowground life forms (Parihar et al., 2020). Mycorrhiza involving a bidirectional exchange of nutrients in the form of photosynthates from plants to fungi and mineral nutrients from fungi to plants significantly influences the host primary productivity and global carbon cycling (Faghihinia et al., 2023). Plants transfer nearly 20% of their photosynthetically fixed carbon to mycorrhizal fungi in the form of hexose sugars and lipids and the mycorrhizal fungi deposits 70% of it into the soil in the form of SOC (Tome at al., 2015). Mycorrhiza contributes sequestration of C in soil under elevated CO_2 and N deposition to the formation of SOC via direct and indirect mechanisms. Mycorrhizal fungi develop vast hyphal networks into the soil matrix which allows them to explore a large volume of the soil extending beyond the range of fine roots which contribute 20-30% of the soil microbial biomass (SMC) (Leake, 2004). The hyphal cell walls are mainly composed of chitin, a carbohydrate polymer which is resistant to microbial decomposition and whose pyrolysis products lasts around for 49 ± 19 years on average. Furthermore, the expected lifespan of mycorrhizal hyphae is only about 5-6 days, resulting in a high hyphal turnover rate (Hagenbo et al., 2017). As a result, the long-term accumulation of hyphal residues in the soil matrix the hyphal biomass contributes approximately 54-900 kg/ha of soil organic carbon which is around 15% of the soil SOC pool and greatly improves soil carbon sequestration (Parihar et al., 2020, Hu et al., 2024). The mycorrhiza also forms water stable soil micro-aggregates by the enmeshment action of the hyphae and also by releasing exudates into the soil matrix. The formation of soil micro-aggregates entraps the SOC within them thereby protecting it from microbial degradation which also aids in the sequestration of carbon in the soil. Mycorrhizae also secrete glomalin, a unique type of glycoprotein, into the soil. Glomalin alone can account for 30-60% of total SOC in undisturbed soils has a significant turnover period in soil, ranging from 6 to 42 years (Guo et al., 2019). This prolonged turnover period underscores the importance of glomalin as a significant contributor to the soil organic carbon (SOC) pool, thereby playing a critical role in the maintenance of soil stability. Furthermore, glomalin demonstrates a positive correlation with the water stability of soil aggregates due to its adhesive property which binds and stabilizes soil particles, which enhances the SOC pool by approximately 27% through the preservation of aggregate stability (Liu et al., 2022). In addition to glomalin, mycorrhizal hyphae release a diverse array of labile carbon compounds, including sugars, amino acids, and organic acids, which directly contribute to the soil organic carbon (SOC) pool (Luthfiana et al., 2021). Mycorrhizae can indirectly improve soil carbon sequestration by facilitating the accumulation of plant photosynthates through the regulation of photosynthetic capacity. This is achieved by increasing leaf area, chlorophyll content, biomass, photosynthesis rate and the respiratory quotient, which trap more CO_2 (Wang et al., 2016). Arbuscular mycorrhizae (AM) employ a rapid nutrient acquisition strategy due to their non-saprophytic nature, rendering them unable to directly obtain mineral nutrients from soil organic matter (SOM). Consequently, to facilitate nutrient uptake, AM fungi interact with saprophytic soil bacteria by exuding carbon-rich compounds into the soil (Basiru et al., 2023). This interaction stimulates the bacteria to accelerate the breakdown of SOM, thereby releasing mineral nutrients and contributing to a reduction in soil organic carbon (SOC) accumulation. This process also results in a net carbon loss, as the decomposition of SOC by saprophytic bacteria surpasses the additional carbon assimilated by AM fungi (Hu et al., 2024). Furthermore, the composition of AM communities significantly influences SOC stocks in the soil, attributable to variations in life history strategies across different AM taxa (Wu et al., 2023). Thus, mycorrhizae are essential organisms within the pedosphere that significantly influence global carbon cycling and carbon sequestration. Their nutrient acquisition strategies, life histories, and community diversity can substantially impact these processes. Ecological strategies that favour specific mycorrhizal types may enhance the carbon sequestration capacity of soils.

Role of AM in reducing release of greenhouse gases other than CO_2

Among the non-carbon green-house gases, Nitrous oxide (N_2O) is a long-lived greenhouse gas with more potential in warming and accelerates ozone depletion (approx. 273 times more than CO_2) (Arias et al., 2021). Half of the human raised N_2O are emitted from (Tian et al., 2020). Nitrification and denitrification process are mainly responsible. N_2O is produced as a byproduct during the decomposition of organic residues. A large amount of crop residues is generated during agricultural production. Recycling of crop residues to mix with agricultural soils provide numerous benefits, as increase soil water retention, nutrient cycling and soil carbon sequestration and can alleviate soil erosion. But the decomposition of crop residues unfortunately can also accelerate higher N_2O emissions which mostly counter the benefit of C sequestration. Evidence suggests that though AMF lacks the enzymes for decomposition. They promote the decomposition and N release of residues, by influencing other microbes and soil structure and utilize the released N for their own growth or transfer some to the host plant (Hodge & Fitter, 2010). AMF acquire one third of their hyphal N in this way. They stimulate the decomposition first of fresh residues, then slow down the rate in degraded residues, and the release of dissolved oxygen content by promoting soil aggregates. This condition suppresses the ammonia-oxidizing bacteria in degraded residues. Ammonia oxidation is mediated by autotrophic organisms in an aerobic process, in which the concentrations of oxygen and the quantity of ammonia (NH_3) influence processing rate. AMF compete with nitrifier microbes for NH_4^- and O_2 and slow down the process. AMF can absorb NH_4^+, NO^{3-}, and some simple organic N from the soil. AMF hyphae proliferated extensively in the half decomposed organic patches and absorb N, preferably, NH_4^+ up to 50% (Li et al., 2023). Enhanced interception of N by mycorrhizal colonized roots, is likely to be associated with root length and densities, reduce N_2O emissions or N loss by leaching or than non-mycorrhizal root systems. AMF confer the potential on roots to immobilize N.

Reducing water footprint

As for fertilizers, water is increasingly valued. Water availability is an increased concern due to climate change, and studies on the area have proposed the concepts of water productivity and water footprint. Water productivity corresponds to the quantity of product obtained using a given water volume (Molden et al., 2010). Water Footprint (WF) is an indicator recently developed to quantify the virtual content of water in products or services (Lovarelli et al., 2016), and it is generally expressed as a ratio of water volume used by the crop (through evapotranspiration) per mass of the agricultural product. Crops can tolerate water stress up to a specific limit, beyond which severe decline in yield is expected. Mycorrhizal crops are more efficient in water use. Beside nutrients, AMF are capable to uptake water from low hydraulic gradient and help plants to endure drought (Auge et al., 2015). Additionally, AMF helps host plants to cope up with other abiotic stresses as temperature. AMF inoculation improve water use and water productivity to keep yield levels even when plants are subjected to water stress (Fracasso et al., 2020). An improvement in soil water retention, which is promoted by hyphal network and glomalin as well as higher water supply is provided by the arbuscular mycorrhizal fungal mycelium network from low water potential and modified stomatal conductance help plants to cope water scarcity in presence of AM. Deficit and optimized irrigation is able to increase crop yield and fruit size in AM inoculated crop.

Conclusion

To maintain a climate smart sustainable agricultural system, AMF hyphal networks need to be strengthening to reinforce the interaction between AMF and soil microbiome, leading to increased water, P and N uptake, biocontrol; thus, limiting energy use in agriculture and carbon sequestration and mitigation of N_2O emissions, However, conventional agriculture practices such as, use of agrochemicals and intensive tillage compromise the benefits of AMF inoculation due to their negative effects on AMF diversity and hyphal network in agricultural soils.

Conflict of interest

The authors declare no conflicts of interest related to the authorship or publication of this book chapter.

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