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Biochar Designed with Secondary Metabolites: Sustainable Agro-Technology against Abiotic and Biotic Stress

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Abstract

Utilization of biochar *i.e.*, solid product obtained through pyrolysis of biomass is captivating global interest in agricultural prospective. Along with reduction in anthropogenic emission of greenhouse gases and bioremediation of natural resources, biochar as a soil amendment also upgrade the nutrient retention, soil tilth and rhizospheric microbial community. To enhance the benign effects of biochar in crop production, designed biochar has been produced by the immobilization of fertilizers and biocontrol agents on biochar according to the specific requirements. Several studies mentioned different virtues of designed biochar that includes antagonistic potential, plant growth promoting attributes and the ability to activate the induced systemic response against foliar pathogens during field trials. Due to complications regarding the efficacy faced by whole organism formulations of biocontrol agents, secondary metabolites has emerged as promising substitute with target specificity, invulnerable to geographical locations, longer shelf life, resistant against climatic conditions and large scale production. Metabolites obtained from biocontrol agents against abiotic and biotic stresses have proved their potential in antagonistic and plant growth promoting abilities. The objective of this article is to devise the combination of biochar with specific metabolites and to glean maximum advantages in our agro ecosystems.

1. Introduction

Availability of quality food for the enormously growing population with continuously constricting arable area due to numerous anthropogenic ventures is one of the major constraints faced by developing countries (Abhilash *et al.,* 2013). Presence of various abiotic stresses such as high temperature, salinity, draught, *etc*. along with biotic stress faced due to different insects, pests, fungal and bacterial pathogens are enhancing burden to the existing circumstances. Noticeable rate of decline in agricultural productivity and the challenges faced during the cultivation of new crops has been mentioned in different studies. Stunted growth has been observed in plants exposed to salt stress in arid and semiarid zones due to increased salt concentration in both soil and irrigating water (Munns, 2002). Numerous reports mention qualitative and quantitative crop loss due to physiological alterations in plants as a resultant of various extreme environmental conditions. Similarly, both pre- and post-harvest plant diseases cover a major portion of crop loss which is a major concern of cultivators for each crop at any time. Various pathogenic fungi, bacteria, nematodes, oomycetes, pests and various other harmful organisms damage the crops and cause loss of agricultural productivity up to 30% (Kumar and Gupta, 2012; Singh *et al.,* 2014; Mishra *et al.,* 2015). Therefore, providing food security with quality crop to enormous population with finite resources along with environmental stability is the preeminent dilemma faced by developing countries.

2. Need of Secondary Metabolites

To handle the above mentioned problem regarding upcoming food crunch, enormous use of agrochemicals was found to be economically dependable alternative basically to prevent crops from biotic stresses and deficiency of nutrients in soil. The unbalanced application of these chemicals resulted in several adverse consequences that encompass resistant pathogenic strains, destruction of pollinators, delayed deterioration which result into aggregation of non-degradable chemicals in ecosystem and hence contamination of food chain. Despite of the efficacy shown by chemical fertilizers in management of diseases, utilization of numerous synthetic compounds has been restricted by government associations due to abominable traits (Strange, 1993; Herr, 1995).

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In order to confront the above mentioned harmful consequences, there was persuasive requirement of safer, economical and ecofriendly substitute for mitigation of biotic and abiotic stresses faced by crops.

This plight drawn the attention of researchers towards biological control measures either alone or with minimal fraction of chemicals as sustainable alternative considered by both agronomist and environmentalist for enhanced plant growth with ecological safety hand in hand (Chet and Inbar, 1994; Harman and Kubicek, 1998). Introduction of agriculturally important microbes with antagonistic effect on pathogenic microorganisms and plant growth promoting attributes is one of the utmost prolific approaches utilized in biological control measures. There are numerous microorganism having biocontrol and plant growth promoting abilities but only few persuasive members from fungus and bacterial families are approved by government agencies as biocontrol agents (BCAs) and have been converted into various formulations (Orietta and Larrea, 2001). Benefits attained by the crops and soil after the application of strain dependent BCAs comprises of management of pathogens, enhanced growth parameters, introduction of impervious microbes in rhizosphere, enhancement in host resistance against stress conditions, increase in accessibility and uptake of nutrients which results in inclusive amelioration of plant health (Harman, 2000; Harman *et al*., 2004; Vinale *et al*., 2008).

Among all the certified biocontrol agents, ubiquitous soil fungi of ascomycete family namely *Trichoderma* is a virulent and opportunistic symbiont which is most commonly isolated and augment the innate defense response of host plants (Sarma *et al.,* 2015; Jain *et al.,* 2012; Spence *et al.,* 2014). The capability of genus *Trichoderma* to parasitize pathogenic fungi along with increase in seedling emanation and elevated aspects of plant growth drive them to be applied as biofungicides (Mukhopadhyay *et al.*, 1992; Mukhopadhyay and Mukherjee, 1996; Chet *et al.*, 1998; Harman and Bjorkmann, 1998; Singh *et al.*, 2016). Biocontrol efficacy is conferred by different mechanism including competition with other microbes for nutrients, mycoparasitism through the degradation of pathogenic hyphal cell wall and antibiosis through secretion of antimicrobial compounds such as antibiotics and various secondary metabolites (van Loon *et al.*, 1998, Sivasithamparam and Ghisalberti, 1998; Keswani *et al*., 2013). Production of different organic acids decreases the pH of soil which results in solublization of different macro and micro nutrients such as phosphorus, iron, magnesium, manganese, *etc*. that conclusively support plant growth (Harman, 2000). The biocontrol efficiency and plant growth promoting capabilities of biocontrol agents are demonstrating observable differences in control and *Trichoderma* treated plants in lab and green house condition but unable to perform at its maximum level during field trials. Numerous reasons are involved for such condition of reduced efficacy faced by biocontrol agents during field trials including different geographical conditions, extreme climatic conditions, wide range of pathogenic microorganisms and competition for nutrients and space with other rhizospheric microorganisms. The protracted procedures from the development of formulations to their application in field also intensify the complications which includes the harsh conditions faced during transport, exposure of treated seeds to direct sunlight during storage, moisture content in formulation and application in fields previously treated with chemical fertilizers that hinders the efficiency of biocontrol agents (Montesenos, 2003; Madhusudhan *et al.,* 2010; Bashan *et al.,* 2014). Secondary metabolites produced by *Trichoderma* can be practiced to combat the challenges faced by whole organism formulations.

3. Secondary Metabolites

Number of studies has mentioned wide varieties and different quantities of secondary metabolites produced by *Trichoderma* with biocontrol and plant growth promoting abilities (Sivasithamparam and Ghisalberti, 1998; Vyas and Mathur, 2002; Keswani *et al*., 2014). Secondary metabolites are strain dependent heterogeneous volatile and non-volatile natural compounds involved in functioning and survival of host organism during abiotic and biotic stress conditions (Stone and Williams, 1992; Demain and Fang, 2000; Keller *et al*., 2005; Reino *et al.,* 2008). These strain dependent compounds are not involved in elemental functioning of host organism but are derived from primary metabolites at certain stage of culture during specific growth condition possessing industrial importance (Herbert, 1989). Different qualitative and quantitative profiling by the help of the liquid and gas chromatography along with mass spectroscopy confirm the enhanced production of defense related and plant growth promoting metabolites during confrontation with pathogenic microorganism (Viterbo *et al.,* 2007; Vinale *et al.,* 2008). Structurally diverse compounds of taxonomical attributes at very minimal concentration can acts as either MAMPs (Microbe Associated Molecular Factors) or elicitors to regulate signal transduction which in turn activate various metabolic and physiological pathways (Frisvad *et al*., 1998; Hoffmeister and Keller, 2007; Karlovsky, 2008; Vinale *et al*., 2008; Osbourn, 2010). A broad spectrum of metabolites including mycotoxins, antibiotics, pigment with antioxidant activities and phytotoxic activities against unwanted growth has already been reported and the list is regularly being upgraded through strain specific metabolomics studies (Macias *et al*., 2000; Vyas and Mathur, 2002). To mention few among them, pyrone possessing coconut aroma exhibit antibiotic, antifungal and plant growth promoting activities along with upregulation of ß-1,3-glucanase and polyphenoloxidase activities in root and shoot tissues of host plants (Simon *et al*., 1988; Scarselletti and Faul, 1994; El-Hasan and Buchenauer, 2009). Koninginins (complex pyranes), Viridin (steroid), Harzianopyridone, (nitrogen heterocyclic compound), Cerinolactone (hydroxyl-lactone derivative), Alamethicin (peptaibol), T22 azaphilones, T39 butenolide, dehydroharzianolide, Trichodermin, dermadin, viridian and isonitriletrichoviridin, (Isocyano metabolites) are few compounds produced by different *Trichoderma* spp. reported to possess antagonistic abilities (Dunlop *et al*., 1989; Di Pietro *et al*., 1993; Howell and Stipanovic, 1994; Wiest *et al*., 2002; Chen *et al*., 2003; Vinale *et al*., 2006, 2012, 2013). Plant growth promotion has been observed in the trials treated with metabolites such as 6PP (6-n-pentyl-6H-pyran-2-one) and harzianolide and has been hypothesized to either act as auxin or elicitors of auxin (Vinale *et al.,* 2008).

4. Biochar: Properties and Needs

Despite of all the benefits such as target specificity, not influenced by geographical conditions, needed in fewer amounts, large scale industrial production and longer shelf life possessed by secondary metabolites, their application to field is quite complicated. Therefore, a stable carrier is needed to regulate the compounds needed in minimal amount for plant growth, stability of volatile compounds, controlled release of metabolites, *etc*. hence the concept of 'designer biochar' can be applied in fields. Biochar is a carbonaceous material obtained by pyrolysing the agricultural biomass such as rice straw, corn stover, peanut shells, *etc*. at 300 to 1000 °C. As the pyrolysis occurs in oxygen deprived conditions, the carbon is retained in the biochar in form of recalcitrant carbon (Xie *et al.,* 2015).

Biochar has collectively contributed as a solution to various environmental issues like water treatment, soil remediation, carbon sequestration, *etc*. Biochar has a well-developed structure with micro and macro pores with high BET surface area due to which it has high capacity for nutrient uptake like ammonium on wheat and rice husk biochar (Saleh *et al*., 2008; Kizito *et al.,* 2015), phosphate (Zeng *et al.*, 2013) and nitrate (Hafshejani *et al.,* 2016). Due to negative surface charge as a result of oxygenated functional groups on biochar, it has strong affinity for the heavy metals like Pb^{2+}, Cr^{6+}, Zn^{2+}, Cd^{2+}, Cu^{2+}, *etc***.** The major mechanisms of uptake are precipitation, ligand exchange, electrostatic attraction, *etc***.** (Ma *et al.,* 2014; Park *et al.,* 2016; Ho *et al.,* 2017). The biochar as a soil ameliorant increases the C:N ratio of soil, thus sequester carbon as increased biomass weight of the plants and also store the recalcitrant carbon for a longer duration in soil (Glaser *et al.,* 2009; Liu *et al.,* 2014). Due to highly porous structure and lesser tensile strength of biochar, its incorporation in the soil reduces the bulk density and increase the pore volume of soil which in turn enhance the root activity and number of root tips *i.e*., indicator of soil health (Lehmann *et al.,* 2011; Langeroodi *et al.,* 2019; Wang *et al.,* 2020). As the biochar ameliorates the physico-chemical properties of soil, it also creates conditions conducive for the survival of microorganisms, thus microbial enrichment at roots zone is found higher in the plants treated with biochar (Warnock *et al.,* 2007; Kwapinski *et al.,* 2010).

5. Designer Biochar: Application and Advantages against Stress Condition

The term designer biochar came in existence to immobilize the required biocontrol agents and fertilizers on modified biochar regarding the requirements for soil management in specific geographical region (Novak *et al.,* 2009; Major, 2010; Głodowska *et al.,* 2016). Soil treated with biochar based nutrient fertilizers are benefitted by higher water and nutrient use efficiency due to high water holding capacity and slow nutrient release properties conferred by Biochar (Gwenzi *et al*., 2018; Hood-Nowotny *et al*., 2018). Number of studies has mentioned the application of biochar along with chemical fertilizer and *Trichoderma* which provided noticeable enhancement in yields and higher biomass as the biochar increase the soil pH to reduce the soil acidity and nutrient availability to the plants (Schulz and Glaser, 2012; Arif Khyber *et al*., 2012; Bruno Glaser *et al*., 2015; Abedin, 2018; Langeroodi *et al*., 2019; Bednik *et al*., 2020). Biochar saturated with nutrients is a potent slow-release fertilizer which has been demonstrated by assistance of SEM and EDX analysis of biochar embedded with NPK in the form of NO_3^-, PO_4^{3-} and K^+ that does not released instantaneously unlike the inorganic commercial fertilizers (Gwenzi *et al.*, 2018). Reports have mentioned the antagonistic and plant growth promoting attributes along with enhanced survivability of biocontrol agent in the biochar combined with *Trichoderma* (Zhang *et al.,* 2016; Elad, 2017; Ribera *et al.,* 2017).

On the basis of studies reporting physical, chemical and microbial improvement in the soil treated with biochar, it is predicted that stress specific secondary metabolites combined with biochar can be safer, economic and ecofriendly agro technological approach for sustainable agriculture as addition of only biochar in different potting mixtures of soil is able to induce induced systemic response in host plant (Elad *et al.,* 2010). In addition, application and market development of biochar can mitigate the environmental stresses and enhance the adaptation to the changing climate. Global gene expression arrays can be utilized to explore the up-regulation of euchromatin regions and signaling molecules from the treated plants on the application secondary metabolites associated biochar (Viger *et al.,* 2015). Future research is focusing on deciphering the unexplored benefits retained by biochar along with specific volatile and nonvolatile metabolites during exposure to abiotic and biotic stresses**.**

6. Conclusion

The ultimate need of the current scenario is to provide quality crop to continuously increasing population with limited natural resources. In order to combat the problematic conditions, unlawful application of chemical fertilizer resulted in detrimental effects on each level of ecosystem. The inclination of researchers towards environmental friendly bioengineered affordable organic fertilizers with better shelf life, target specific, impassive by geographical conditions, resistant to climatic conditions and ease of large scale production for plant growth promotion and disease management has thus become the urgent requirement of the hour. The hindrances faced by whole organism formulation can be overcome by the development of ready-to-use formulation of biochar along with secondary metabolites during stress conditions. Numbers of strain specific secondary metabolites such as glucosinolates, flavonoids, antibiotics and phenols are produced by different biocontrol agents during their confrontation with abiotic and biotic stresses which work as molecular effectors to activate the defense mechanism in host plants. Future research should be directed towards the development of potential bioengineered organic fertilizers along with suitable carrier at commercial level to accomplish the need of higher efficacy for crucial crops and maintain a sustainable agro ecosystem. Fascination towards the application of biochar in agricultural sector has increased as a potent soil rehabilitator in physical, chemical and biological aspects along with reduction in anthropogenic emission of greenhouse gases and bioremediation of natural resources. Immobilization of stress metabolites on biochar *i.e*., designer biochar needs to be exploited for better understanding to attain the protection against pathogenic strains and enhanced level of crop yield by manipulating rhizospheric biology and their microclimate. Three-way cross talk between plant, soil and designed biochar need to be investigated thoroughly to determine a defined biochar application rates in both model and crop plants for real time analysis for regulation of defense and growth promoting genes.

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