Biochar Mitigates Salinity Stress in Plants

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Abstract

Salinity is a major problem in India. It not only hampers the growth of plant and productivity but also decreases the soil productivity. Some plants develop several mechanisms to cope up Salinity stress like ion regulation by Na/H antiporter; synthesis of amino acids like valine, aspartic acid, and proline; etc. Various antioxidants play crucial role in combating salinity stress. Biochar (product obtained after pyrolysis of any organic compound) enhances the fertility of soil as it improves the soil cation exchange capacity and water holding capacity. That in turn improves the nutrient capacity of the soil. A biochar property is also dependent on the type of material and pyrolysis temperature. After biochar amendment to the saline soil, its physicochemical parameters improve like organic carbon, CEC, available phosphorous, etc. Thus, biochar not only enhances the crop productivity but also improves soil enzymatic activity.

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6.1   Introduction

The genesis of biochar is linked to the ancient Amerindian populations of the Amazon region, regionally known as Terra Preta de Indio, where dark earth was created through the use of slash-and-char techniques (Lehmann 2009; Lehmann and Joseph 2009a). Research on Terra Preta soils (hortic anthrosols) discloses various effects of biochars on the functionality of soils in the Amazonia. Generally, biochar ameliorates with the soil for maintaining soil fertility and sustainability. Biochar is also recognized as a very crucial tool for the management of the environment (Lehmann and Joseph 2009b). Biochar is a newly fabricated scientific term, which means a carbon (C)-rich product is obtained when organic substance like agricultural residues. Wood or manure is heated in a closed chamber in absence of air or little air (Lehmann and Joseph 2009a). Further, Shackley et al. (2012) defined biochar more precisely as "the porous carbonaceous solid material generated by the thermochemical conversion of organic materials in an anaerobic atmosphere that owns physicochemical properties suitable for safe and long-term storage of carbon in the environment." The International Biochar Initiative (IBI) standardized its definition as "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" (IBI 2012). All of these definitions are directly or indirectly related to the biochar production condition and its application to soil. Lehmann and Joseph (2009b) differentiate biochar operationally from charcoal. Chiefly, the difference lies in the end use of biochar and charcoal. Charcoal is used for producing fuel and energy, and basically it is a charred organic matter, whereas biochar is usually applied for carbon sequestration and environmental management. The term hydrochar is closely related to biochar; however, it is distinguished by different conditions like the hydrothermal carbonization of biomass (Libra et al. 2011). Broadly, biochar is generated by dry carbonization or pyrolysis and gasification of biomass, whereas hydrochar is produced as slurry in water by hydrothermal carbonization of biomass under pressure. These two chars varied widely in physical as well as chemical properties (Bargmann et al. 2013). Four major areas where biochar is being used in environmental management are (1) soil reclamation, (2) waste management, (3) climate change mitigation, and (4) energy generation (Lehmann and Joseph 2009a).

6.2   Biochar Properties

6.2.1   Biomass Pyrolysis

Biomass resources may be limited for the biochar production in a sustainable way. For example, biomass obtained from agricultural crops and trees (forests) may cause diminution of forest areas and increase soil erosion, hence decreasing soil fertility (Cowie et al. 2012). To overcome this situation, Brick (2010) categorized feedstocks into two groups: (1) primarily produced biomass as a resource of bioenergy and biochar and (2) by-products as waste biomass. Nowadays, waste biomass

Table 6.1 Pyrolysis processes and its end products

Process	Residence time	Products (%)		
		Liquid (bio-oil)	Solid (biochar)	Gas (syngas)
Fast (temperature around 300–1000 °C)	Less than 2 s	75%	12%	13%
Intermediate (temperature near about 500 °C)	Moderate residence time	50%	25%	25%
Slow (temperature around 100–1000 °C)	Long residence time	30%	35%	35%
Gasification (temperature more than 800 °C)	Moderate residence time	5% tar	10%	85%

has been used extensively for production of biochar because of its cost-effectiveness and food security advantages compared to other types of biomass (Brick 2010). Biochar is usually made by thermochemical decomposition of biomass at temperatures between 200 and 900 °C in anaerobic condition, which is commonly known as pyrolysis (Demirbas and Arin 2002). Pyrolysis is further categorized into fast, intermediate, and slow depending on the residence time and temperature (Table 6.1; Mohan et al. 2006). Fast pyrolysis process have a short residence time (less than 2 s) and usually generate about 75% of bio-oil from biomass (Mohan et al. 2006). Biochar production around 25–35% comes from slow and intermediate pyrolysis procedure which has a residence time between a few minutes and several hours (Brown 2009).

Gasification is different from general pyrolysis process. In gasification, organic biomass is transformed into gases which are usually rich in carbon monoxide and hydrogen; this is obtained when biomass is burned at high temperature (more than 800 °C) in a controlled aerobic environment. The resulting gas mixture is known as synthetic gas or syngas (Mohan et al. 2006; Sohi et al. 2009).

6.2.2   Factors Affecting Biochar Properties

There are various factors that affect biochar properties, and they are feedstock type, pyrolysis temperature, and heating rate. Table 6.2 showed various types of feedstock and biochar properties.

Commonly, animal litter and solid waste produced a large amount of biochar compared to the biochar obtained from agricultural fields and wood biomasses (Enders et al. 2012). The high yield is associated with the higher inorganic constituents of the raw materials, as indicated by their high ash content. Biochar derived from animal litter contains inherent metals which protect the biochar material from the loss of volatile matter present in biochar by charging the bond dissociation energies of organic and inorganic C bonds (Cantrell et al. 2012). This finding supported by Raveendran et al. (1995) also suggested that high-yield biochar was obtained from rice husk, groundnut shells, coir pith, and wheat straw due to the higher levels of K and Zn. Usually, materials with high lignin percent produce good amount of

Table 6.2 Characteristics of biochar derived from different feedstock

Feedstock	Pyrolysis temperature °C	Heating rate °C min⁻¹	Yield (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	Surface area (m² g⁻¹)	References
Rapeseed	500	5.0	35.6	12.9	75	2.62	7.79	1.41	15.7	Karaosmanoğlu et al. (2000)
Rapeseed	600	5.0	32.2	13.9	78.48	1.88	3.94	1.53	17.6	Karaosmanoğlu et al. (2000)
Rapeseed	700	5.0	29.6	14.4	79.48	1.20	3.29	1.35	19.3	Karaosmanoğlu et al. (2000)
Pine needles	300	–	48.6	1.9	68.87	4.31	25.74	1.08	19.9	Chen et al. (2008)
Pine needles	500	–	26.1	2.8	81.67	2.26	14.96	1.11	236.4	Chen et al. (2008)
Pine needles	700	–	14	2.2	86.51	1.28	11.08	1.13	490.8	Chen et al. (2008)
Swine solid	620	13	43.49	44.7	50.70	1.9	0.01	3.26	–	Ro et al. (2010)
Boiler litter	350	–	–	–	45.60	4	18.30	4.50	60	Uchimiya et al. (2010)
Boiler litter	700	–	–	–	46	1.42	7.40	2.82	94	Uchimiya et al. (2010)
Soybean straw	400	20	24.7	–	44.10	–	–	2.38	–	Tong et al. (2011)
Swine solid	700	8.3	36.4	52.9	44.06	0.74	4.03	2.61	4.1	Cantrell et al. (2012)
Wheat straw	400	8.0	34	9.7	65.70	4.05	–	1.05	4.8	Kloss et al. (2012)
Wheat straw	525	8.0	34	9.7	74.40	2.83		1.04	14.2	Kloss et al. (2012)

biochar (Sohi et al. 2010a). Increased heating rate from 5 to 15 °C min⁻¹ showed a slight decrease in biochar yield (Karaosmanoğlu et al. 2000). Pyrolysis temperature plays an influential role in determining biochar characteristics. In a study on cottonseed hulls, Uchimiya et al. (2011a) revealed that the biochar yield was affected by the pyrolysis temperatures. A swift reduction in biochar generation was found at more than 400 °C because of the loss of volatile matter and noncondensable gases (CO_2, CO, H_2, and CH_4). The biochar yield was stable at less than 400 °C in cottonseed hulls due to low lignin content. A quick decline in biochar yields was observed at more than 300 °C due to initial degradation reactions, in the case of biochar obtained from grass and wood materials (Keiluweit et al. 2010). However, lignin content of grass is less than the lignin content of wood which causes thermal breakdown at low temperature (200–400 °C).

An enhanced temperature during pyrolysis increases the carbon content, whereas hydrogen and oxygen contents were decreased (Table 6.2). This results in lower molar H/C and O/C ratios, thereby indicating dehydration and deoxygenation of the biomass (Keiluweit et al. 2010). Biochar derived from sewage sludge and poultry manure does not undergo depolymerization due to the absence of lignocellulosic compounds. They are generally rich in N content. Regarding other elements, insufficient database is available for S and P contents of biochar. Usually, no significant change was observed in pyrolysis temperature of various feedstocks (Table 6.2) related to N content of biochar obtained from various sources. S containing functional groups (present in biochar) increases ammonia retention on the surface of char due to ammonium sulfate salts (Petit et al. 2010). Hence, the functional groups in biochar affect the nutrient cycling in soil. Pyrolysis temperature highly influences the morphology and surface structure in biochar (Liu et al. 2010; Uchimiya et al. 2011a). In general, increase in pyrolysis temperature enhances the surface area of char. Although at 700 °C a reduction in surface area has also been reported (Uchimiya et al. 2011b). At high pyrolysis temperature, the aliphatic alkyl and ester groups are disrupted or dissolved which exposes the aromatic lignin core which may be responsible for an increase in surface area (Chen and Chen 2009). Downie et al. (2009) suggested that the pore size distribution is a key factor responsible for the increase in surface area in biochar. Biochars obtained from animal litter and solid waste displayed lower surface areas, whereas biochars obtained from crop residue and wood biomass showed higher surface area even at high temperatures (Table 6.2). This may be due to the low C content and high molar H/C and O/C ratios in the latter biomass samples, leading to the formation of extensive cross-linkages (Bourke et al. 2007; Ahmad et al. 2014a).

6.3 Physiological and Biochemical Response of Plant Under Salt Stress

Salinity is the most important environmental factor that limits plant growth and productivity (Allakhverdiev et al. 2000). The harmful effects of high salt content on plants can be observed such as reduced growth or the death of plants. Many plants

create different ways to eliminate salt from their cells or to agglomerate the salt in the cells. During the initiation and development of the salt stress within a plant, all crucial processes such as photosynthesis, protein synthesis, and energy and lipid metabolism are strongly affected. The prompt response is to reduce the speed of blade surface expansion, followed by a termination of expansion as the stress increases. The growth of the plant increases again when the stress is relieved. The photosynthetic rate is generally lower for plants under salt stress.

6.3.1   Salt Tolerance of Plants

Plants which are salt tolerant have a capability to grow and complete their life cycle on a medium containing high amount of salts. Plants that sustain high concentrations of salt in their rhizospheric zone and grow well are known as halophytes. Depending on their salt tolerance, halophytes are obligate or facultative. Obligate halophytes are characterized by low morphology and taxonomic diversity with relatively higher growth rates. In facultative halophytes, they are found in less healthy habitats along the border between saline and nonsaline lands and characterized by a greater physiological diversity that allows them to cope with saline conditions and nonsaline situations.

6.3.2   Mechanism Adopted by the Plant Against Salt Tolerance

Plants follow a series of molecular and biochemical strategies to deal with salt stress. Biochemical processes leading to various products which in turn stimulate various processes that help the plants to cope up with the salinity stress (Iyengar and Reddy 1996). Biochemical mechanism includes (1) selective agglomeration or elimination of ions, (2) selective ion uptake by the roots and transfer it to the leaves, (3) compartmentalization and fixation of ions at the cellular levels, (4) production of various compatible solutes, (5) alterations in photosynthetic pathway, (6) alteration in membrane structure, (7) stimulation of various enzymatic and nonenzymatic antioxidants, and (8) induction of plant hormones. Salt tolerance mechanisms operated inside the plants are generally low complex or high complex. Low-complex mechanism involves alterations in various biochemical pathways. High-complex mechanisms involve changes in crucial process like chromosomal structural changes, viz., DNA methylation and DNA elimination (Walbot and Cullis 1985), and in photosynthesis and respiration processes, i.e., water use efficiency and plasma membrane–cell wall interactions (Botella et al. 1994). It is usually found that high-complex mechanism works in coordination with low-complex mechanism (Bohnert et al. 1995).

6.3.2.1 Ion Modulation and Compartmentalization
Plant generally restricts salt uptake under saline condition or compartmentalizes the salts within various tissues (Adams et al. 1992). Plants, whether glycophyte or halophyte, cannot sustain high concentration of salts within the cytoplasm, and thus they

are confined within the vacuole or fix the ions in various tissues to promote normal metabolic functions of the cell (Reddy et al. 1992; Iyengar and Reddy 1996; Zhu 2003). Cheeseman (1988) reported that glycophytes restrict Na uptake or store them in eldest tissues which will eventually be sacrificed (Cheeseman 1988). Salt-inducible enzymes expel sodium from the cytoplasm or confined within the vacuoles and this is usually done by a Na^+/H^+ antiporter (Apse et al. 1999). Two types of electrogenic H+ pumps exist. The first one is vacuolar-type H^+-ATPase (V-ATPase) and the second one is vacuolar pyrophosphatase (V-PPase). Dietz et al. (2001) reported that H^+ pumps work in a synchronized way and exist at the membranes of secretory pathways of plants. V-ATPase is the dominant H^+ pump found at the endo-membranes of most of the plant cells. Under normal conditions, the V-ATPase is imperative for plant growth because it provides energy to secondary transport, maintains solute homeostasis, and also enhances vesicle fusion. During abiotic stress conditions like salinity, drought, anoxia, excess heavy metals, etc. in the soil, survival of the plant cells largely resides on retaining the activity of the V-ATPase. Modulation of gene expression and its activity based on the V-ATPase adapting capability lies on long- and short-term bases. A study by Otoch et al. (2001) on salt stress in hypocotyls of *Vigna unguiculata* seedlings revealed that tonoplast regulates salt by H^+-pumping, V-ATPase, and H^+-pyrophosphatase. During salt stress, V-ATPase activity was enhanced, whereas V-PPase activity was restricted (Otoch et al. 2001). The crucial mechanism in halophytes (*Suaeda salsa*) against salinity stress is the modulation of V-ATPase activity, which in turn activates the tonoplast to facilitate ion uptake inside the vacuole; however, V-PPase plays a secondary role (Wang et al. 2001). When the plant is under salt stress, it maintains high concentrations of K^+ and lower concentrations of Na^+ in the cytosol. This is maintained by K^+ and Na^+ transporters, and the driving force for transport is generated by H^+ pumps (Zhu et al. 1993). Some salt stress sensors have been identified which help sustain the plant during stress. Zhu et al. (1993) demonstrated that calcium signal activates the myristoylated calcium-binding protein SOS3 and the serine/threonine protein kinase SOS2. This protein kinase complex then phosphorylates and triggers various ion transporters, such as the plasma membrane Na^+/H^+ antiporter SOS1. *Arabidopsis thaliana* (AtNHX1 gene) encodes a vacuolar Na^+/H^+ antiporter which is crucial for salt tolerance. A similar study by Shi and Zhu (2002) reported modulation of AtNHX1 expression along with ABA production during salt stress. Experimental evidence revealed that salts like NaCl, KCl, or ABA modulate the level of AtNHX1 transcript. AtNHX1 promoter (GUS) analysis in transgenic *Arabidopsis* displayed that AtNHX1 is expressed in all plant tissues except the root tip. High GUS expression was observed in guard cells which further disclosed that AtNHX1 played crucial role in regulation of K+ homeostasis into the specialized cells. NaCl, KCl, or ABA regulates the expression of AtNHX1 at the transcriptional level. AtNHX1 store Na^+ in the enlarged vacuoles of the root hair cells.

Studies (Liu and Zhu 1997; Lauchli and Schubert 1989) showed that Ca^{2+} plays a major role in salt adaptation by the plants. It also stimulates K^+/Na^+ transporters. High salinity also induces high cytosolic Ca^{2+} which is shifted from the intracellular compartments and apoplast (Knight et al. 1997). The resultant transient Ca^{2+}

increase potentiates stress signal transduction and leads to salt adaptation (Mendoza et al. 1994; Knight et al. 1997). Other strategies of salt modulation are salt secretion and selective salt agglomeration or elimination. Salt secretion takes place with the help of unique cellular structure known as salt glands. Salts are expelled from these glands from the leaf surface and maintain ion concentration inside the cell (Hogarth 1999). Salt ejection occurs through the roots in many halophytes (Levitt 1980). Selective agglomeration of ions enables the plants to make osmotic adjustments which results in enhanced water retention and Na exclusion.

6.3.2.2 Induced Biosynthesis of Compatible Solutes

The cytoplasm cumulates low molecular mass compounds known as compatible solutes to harmonize ionic balance in vacuoles, as it does not disrupt the normal metabolic reactions rather it replaces water from the biochemical reactions (Yancey et al. 1982; Ford 1984; Ashihara et al. 1997; Hasegawa et al. 2000; Zhifang and Loescher 2003). Osmolytes maintain the osmotic balance of the tissues by water influx (or reduced efflux) to protect plant structure from salt stress. Compatible solutes contain mainly proline (Khatkar and Kuhad 2000; Singh et al. 2000), glycine betaine (GB) (Rhodes and Hanson 1993; Khan et al. 2000; Wang and Nil 2000), sugars (Kerepesi and Galiba 2000; Bohnert and Jensen 1996; Pilon-Smits et al. 1995), and polyols (Ford 1984; Popp et al. 1985; Orthen et al. 1994; Bohnert et al. 1995). Polyols have various functions, viz., as low-molecular-weight chaperones and also act as scavengers of oxygen radicals (stress-induced) (Smirnoff and Cumbes 1989; Bohnert et al. 1995). There are two types of polyols: acyclic (e.g., mannitol) and cyclic (e.g., pinitol). Mannitol serves as a compatible solute to deal with salt stress, as it is produced through the action of a mannose-6-phosphate reductase (M6PR) in celery. A bacterial gene is used to engineer mannitol biosynthesis in plants to make up the plants to cope salt stress. For example, *A. thaliana* (nonmannitol-producer) has been introduced with M6PR gene under control of the CaMV 35S promotor. After transformation, *Arabidopsis* M6PR transformants started accumulating mannitol throughout the plants, and it ranges between 0.5 and 6 mmol g-1 fresh weight. A unique compound (i.e. mannitol), neither found in celery or *Arabidopsis*. In the absence of NaCl, all transformants are phenotypically the same as the wild type; however, in the presence of NaCl, mature transgenic plants show a high level of salt tolerance (Zhifang and Loescher 2003). Salt stress enhances various reducing sugars like glucose, fructose, sucrose, and fructans in various plants (Kerepesi and Galiba 2000; Khatkar and Kuhad 2000; Singh et al. 2000). However, Gadallah (1999) reported decreased soluble and hydrolyzable sugars in *Vicia faba* due to salinity. Alamgir and Ali (1999) revealed that enhanced sugar content was observed in some genotypes of rice; however, reduction in sugar content was also observed in some genotypes under salinity stress. During salinity stress, Parida et al. (2002) reported that a decrease in starch content vis-a-vis an enhanced content of both reducing and nonreducing sugar has been found in the leaves of *Bruguiera parviflora*. Other studies (Khavarinejad and Mostofi 1998) illustrated that the content of soluble sugars and total saccharides in tomato was increased, but the starch content was not affected by NaCl treatment. Similarly, Gao

et al. (1998) have reported upraised sucrose content along with sucrose phosphate in tomato (*Lycopersicon esculentum* L.), but reduction in acid invertase activity was observed due to salinity stress. A number of nitrogen-containing compounds (NCC) are agglomerated in the plants when subjected to salinity stress. The most common NCC is polyamines, amides, quaternary ammonium compounds, imino acids, and proteins. The specific NCC accumulation varies from plant to plant. Wang and Nil (2000) found that during salt stress, glycine and betaine content increase in various plants. Parida et al. (2002) also confirmed that the proline content is also known to increase under saline condition in the leaves of *B. parviflora*.

Amino acid like cysteine, arginine, and methionine contents were reduced in wheat plants due to NaCl treatments. However, proline, isoleucine, aspartic acid, and valine contents were enhanced in the salinity stress condition (Elshintinawy and Elshourbagy 2001).

6.3.2.3 Induction of Antioxidative Enzymes

Salt stress introduces water paucity due to osmotic effects on various metabolic activities (Greenway and Munns 1980; Cheeseman 1988). This condition leads to the formation of reactive oxygen species (ROS) such as superoxide (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl radical (OH) (Halliwell and Gutteridge 1985), and singlet oxygen ($^1O_2$) (Elstner 1987). These reactive oxygen species (ROS) can cause severe injury to the normal metabolism via lipid peroxidation (Fridovich 1986; Wise and Naylor 1987) and damage to protein and nucleic acids (Fridovich 1986; Imlay and Linn 1988). O_2 concentration is very high during photosynthesis; thus, the chloroplast is more likely to generate ROS (Asada and Takahashi 1987). Superoxide (O_2^-) dismutates, either enzymatically or nonenzymatically, to produce H_2O_2 and O_2. Further, H_2O_2 may interact with certain metal ions or metal chelates to produce highly reactive ˙OH (Imlay and Linn 1988). Plants are equipped with a series of antioxidants to protect themselves from reactive oxygen species. The metalloenzyme superoxide dismutase (SOD) converts O_2^- to H_2O_2. Catalase and a variety of peroxidases (Chang et al. 1984) activate the catalysis of H_2O_2. However, catalase is absent in the chloroplast; H_2O_2 can be detoxified by an ascorbate-specific peroxidase (through the ascorbate–glutathione cycle) that is present in high concentration in this organelle (Chen and Asada 1989; Halliwell and Gutteridge 1986; Asada 1992). Plants that have high levels of antioxidants (either constitutive or induced) have been reported to cope up better against the oxidative damage. The enhanced activities of various antioxidative enzymes such as catalase (CAT), ascorbate peroxidase (APX), guaiacol peroxidase (POD), glutathione reductase (GR), and superoxide dismutase are in correlation with the high levels of salinity stress (Benavides et al. 2000; Lee et al. 2001; Mittova et al. 2003). Comba et al. (1998) revealed that soybean root nodules under salt stress showed decline of ascorbate peroxidase and glutathione reductase activities, whereas superoxide dismutase and reduced glutathione content were increased, and malondialdehyde (MDA) and total protein content remain unchanged. Willkens et al. (1997) reported that tobacco plant displayed enhanced sensitivity against salinity stress. Studies (Orr and Sohal 1992; Allen et al. 1997; Noctor and Foyer 1998) revealed that transgenic plants showed overexpression of genes which

leads to enhanced activities of Mn-SOD, Fe-SOD, chloroplastic Cu/Zn-SOD, bacterial catalase, and glutathione S-transferase (GST)/glutathione peroxidase (GPX) under salinity stress (Roxas et al. 2000). Takemura et al. (2002) observed that salt stress causes stimulation of superoxide in the cytosol which in turn builds up the tolerance capacity of plants (*B. gymnorrhiza*).

6.3.2.4 Stimulation of Plant Hormones

A huge amount of salt stimulate plant hormones like ABA and cytokinins (Vaidyanathan et al. 1999). Abscisic acid is liable for the changes in salt stress-induced genes (De-Bruxelles et al. 1996). Gupta et al. (1998) suggested that in rice, ABA-induced genes play critical role in salt tolerance. An enhanced level of ABA, aminocyclopropane-1-carboxylic acid, and ethylene was observed in *Citrus sinensis* (GomezCadenas et al. 1998) during salt stress. ABA lightens the stress generated due to NaCl (Popova et al. 2002). ABA favors stomatal closure by swiftly changing ion fluxes in guard cells under stress conditions. ABA is also involved in modifications of gene expression and the diversity of potential cis-acting regulatory elements. Chen et al. (2001) demonstrated the experimental evidence which showed that the enhanced Ca^{2+} uptake is correlated with high levels of ABA under salt stress which further maintain membrane integrity. GomezCadenas et al. (2002) reported that ABA caused diminution of ethylene release and leaf absorption in citrus under stress. This is probably due to the decrease in the accumulation of Cl^- ion in the leaves. Salt tolerance of facultative halophytic (*Lophopyrum elongatum)* and less salt-tolerant wheat (*T. aestivum* L.) increased in due course of time, when they are gradually acclimatized with the salt condition rather than suddenly shocked (Noaman et al. 2002). This acclimation to salt stress is regulated by ABA.

6.3.2.5 Change in Photosynthetic Pathway

A high salt concentration inhibits the photosynthesis by reducing the water potential. To cope up from this, plants enhance their water use efficiency under salt stress. Facultative halophytic plants such as *M. crystallinum* change their C3 mode to CAM photosynthesis, so as to reduce their water loss by facilitating the opening of stomata at night (Cushman et al. 1989). Plants like *Atriplex lentiformis* change their mode of photosynthesis from C3 to C4 pathway in response against salinity stress (Zhu and Meinzer 1999).

### 6.3.2.6 Molecular Mechanism of Salt Tolerance

Metabolic adaptation at cellular level makes the plant to sustain against salt stress, and a large number of genes have also been identified that copes the plant against stress (Ingram and Bartels 1996; Bray 1997; Shinozaki et al. 1998). Salt tolerance is a multigenic trait, and various genes having different functional groups are responsible for encoding salt stress proteins: (1) genes for photosynthetic enzymes, (2) genes for synthesis of compatible solutes, (3) genes for vacuolar-sequestering enzymes, and (4) genes for radical scavenging enzymes. Majority of the genes in the functional groups have been classified as salt inducible under stress conditions. Wu et al. (1996) identified mutants by a salt hypersensitivity assay in *Arabidopsis*,

which caused K uptake due to salt stress. Kawasaki et al. (2001) investigated the transcript regulation in rice-tolerant variety Pokkali with microarrays. Adjustment of microorganisms to particular environmental stress is deeply related to the expression of various genes present in the microorganism. Kanesaki et al. (2002) found that hyperosmotic stress showed different effects on the cytoplasmic volume and gene expression in *Synechocystis* sp. PCC 6803. DNA microarray analysis revealed that salt stress stimulates genes for some ribosomal proteins. However, hyperosmotic stress also strongly triggers the genes for 3-ketoacyl-acyl carrier protein reductase and rare lipoprotein A. Each kind of stress stimulates a number of genes for proteins of unknown function.

6.4   How Biochar Mitigates Salinity Stress in Plants

The world population is increasing at an alarming rate and is expected to reach 9.6 billion by 2050 (FAO 2009). Increased population puts pressure for food requirement, and generation of more food in turn creates pressure on natural resources. Agricultural crops are usually subjected to abiotic stresses like salinity, drought, and heavy metal stress (Osakabe et al. 2014; Parihar et al. 2015; Rizwan et al. 2016a). Among the abiotic stresses, salinity and drought are the most serious threats to agricultural production. According to Wicke et al. (2011), more than 1100 million hectares (1128 Mha) of land surface is affected by salinity. Due to salinity problem, approximately an annual economic loss of 27.2 billion USD in terms of crop loss in irrigated agriculture land (Qadir et al. 2014). Loss in revenue increased day by day, and it will reach up to 69% if no precautionary measure is taken to mitigate the deteriorated land. However, the C emanation from degraded lands enhances the cost of reclamation. Plants under salinity have to deal with two types of stresses: one is osmotic stress and the other is ionic stress. The osmotic stress raises the salt level in the soil solution which surrounds the roots that results in water uptake hindrance and interferes in lateral bud development (Munns and Tester 2008). On the other hand, in ionic stress, when Na^+ concentration is more than the threshold, it leads to leaf mortality, chlorosis, necrosis, and inhibition of photosynthesis (Glenn et al. 1999; Panuccio et al. 2014). Biochar is a charcoal-like material gathered after heating any organic material in anaerobic condition (process known as pyrolysis). It has a great demand in the agricultural sector as it enhances the soil physicochemical properties (e.g., soil water holding capacity, aggregate stability, aeration, bulk density, nutrient holding capacity, EC, pH, surface area, and CEC) when amended with degraded soil (Lehmann and Joseph 2009a; Sohi et al. 2010b; Andrenelli et al. 2016; Bamminger et al. 2016). The overall mean increase in crop productivity due to increased plant growth and biomass reported in the literature with biochar amendment was about 10–12% (Jeffery et al. 2011; Haider et al. 2015; Kim et al. 2016). Some studies have shown negative effects on crop productivity when biochar was added in the soil, which may be due to specific types of biochar (Liu et al. 2013). Biochar consists of a large degree of recalcitrant carbon (C) (Cheng et al. 2008), which may remain in the soil for 100–1000 years, and thus, biochar could be very
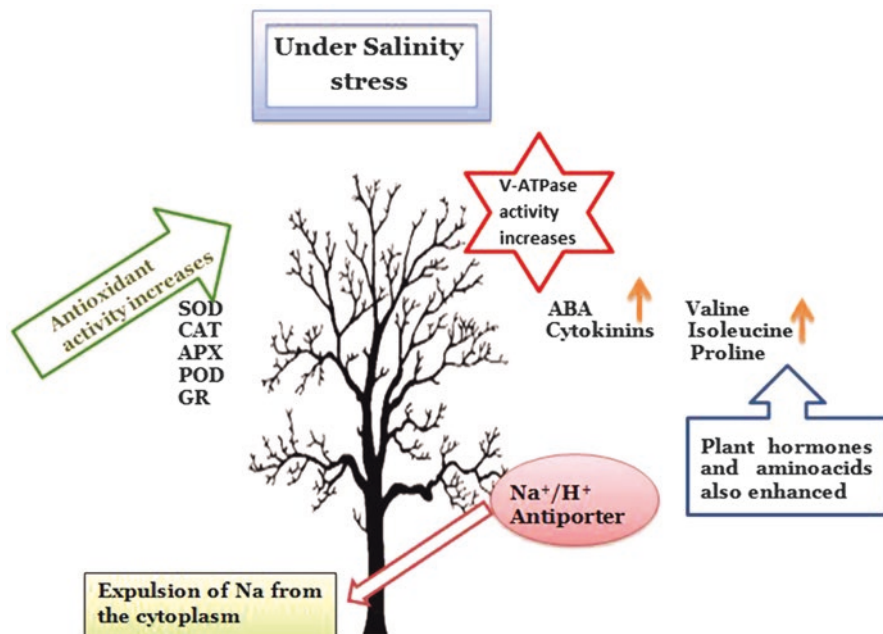
Fig. 6.1 General strategies used by the plants to cope up from salinity stress

effective in fixing the carbon in the soil and hence reducing global greenhouse gas (GHG) emission (Lehmann 2007; Sohi et al. 2010a; Chowdhury et al. 2014). There are plenty of reports which illustrate the remediation of toxic/contaminated soils (Beesley et al. 2011; Uchimiya et al. 2012; Zhang et al. 2013; Ahmad et al. 2014b; Samsuri et al. 2014). The crucial factor or mechanism behind the reclamation of contaminated soil with biochar was due to its high adsorption capacity (Samsuri et al. 2014; Zhang et al. 2013). Thomas et al. (2013) also reported high salt sorption potential of biochar, and therefore, it can alter the negative consequences of salinity by reducing Na^+ uptake or by eliminating Na^+ from the plant cells. The adsorption capacity of biochar is mainly governed by the characteristics of biochar (Lehmann and Joseph 2009a) and the type of feedstock and also the pyrolysis conditions under which the biochar is produced (Chen et al. 2011). The determining feature of biochar which makes it jack of all trades is the high adsorption capacity which includes its high surface area and cation exchange properties (Fig. 6.1).

6.4.1 Functional Properties of Biochar

Adsorption capacity of biochar is mainly because of the presence of functional groups generated during the pyrolysis process which in turn depends on raw material (feedstock) and the pyrolysis temperature (Chun et al. 2004; Ahmad et al. 2012). During pyrolysis at temperature around 300 °C, organic material loses various

degradable compounds such as cellulose and lignin. As the temperature is intensified, the aromatic compounds become more condensed which leads to enhanced surface area of biochar (Inyang et al. 2016). The functional properties of biochar which are derived from agricultural residues can be assessed through FTIR, Boehm titrations, and scanning electron microscopy (Zhang and Luo 2014). Other studies by Zhang et al. (2014) found that the functional properties like carboxyl, lactones, and phenolic groups were observed more in wood-derived biochar than the biochar obtained from bamboo, rice husk, and rice husk ash. A similar study by Qayyum et al. (2012) illustrated high aromaticity in biochar derived from wood as compared to biochar derived from sewage sludge. Biochar derived from pine needles contains various functional groups (Ahmad et al. 2013). The presence of these and other functional groups in biochar makes them a suitable and economical choice for the adsorption of various salts present in the soils, thus mitigating the salinity of the soil (Ahmad et al. 2014a; Rajapaksha et al. 2016).

6.4.2   Salt Stress Effect on Soil Properties

Salt stress negatively affects the soil properties, plant growth, and overall productivity of plants (Ohashi et al. 2014; Rath and Rousk 2015). Commonly, salt-affected soils are further divided into saline, sodic, or saline–sodic which are mainly based on their electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP) of the saturated paste extracts (Richards 1954). Among these three, the saline–sodic soils are highly deteriorated and deprived of nutrient which in turn corresponds to least productivity (Rengasamy and Olsson 1991). Salinity is inversely proportional to the soil properties such as organic matter and C:N ratio (Morrissey et al. 2014). Due to salinity and sodicity, the microbial biomass and microbial activity alter in the soil and gradually decline (Yan et al. 2015). A similar study was done by Rath and Rousk (2015); they found that soil respiration and soil microbial enzyme activities were restricted due to short- or long-term salinity and it also affects the C and nutrient cycling in the soil. However, the net respiration also depends on the residue properties. The adverse consequences of salinity are more prompt in the degraded or infertile soil having materials that are less degradable (Hasbullah and Marschner 2014).

6.4.3   Biochar Effect on Soil Properties Under Salt Stress

Biochar is well known to enhance the plant tolerance against salt stress. Amelioration of soil with the help of biochar was studied extensively; it improves the physico-chemical properties of soil. Studies (Chaganti et al. (2015), Diacono and Montemurro (2015), Sun et al. (2016)) revealed that biochar not only improves the soil characteristics but also related to sodium removal as sodium leaching and EC. Biochar also rectifies the physical, chemical, and biological properties of soil under abiotic stresses (Rizwan et al. 2016b). Lu et al. (2015) reported during maize cultivation,

when biochar derived from poultry manure compost (BPC) amended in saline soil showed increased microbial biomass carbon content and along with the enhanced activities of urease, invertase, and phosphatase in rhizospheric soils. Similar studies were done by Bhaduri et al. (2016); they illustrated that saline soil mitigation by biochar depends upon the amount of biochar, incubation time, biochar material, and type of soil enzymes. However, an organic amendment also improves the physicochemical properties of saline soil (Wang et al. 2014a, b). Not much literature is available on the effect of biochar on the saline soil properties. Thomas et al. (2013) showed that application of biochar (30 g m^{-2}) on salt-affected soil did not alter the pH, although increase in EC was observed over the control. Similarly, enhanced SOC and CEC were observed after furfural biochar was applied in saline soil (Wu et al. 2014). Biochar enhanced the soil organic matter along with the CEC and inhibited the exchangeable Na (Luo et al. 2017). Aforesaid studies showed that addition of biochar in saline soils mitigates the salinity in soil and also enhances the soil microbiota.

6.4.4 Regulation of Stomatal Conductance and Reduction in Oxidative Stress

Various studies (Akhtar et al. 2015a; Lashari et al. 2015) revealed that biochar reduces salt stress in plants by lower production of phytohormones. Akhtar et al. (2015a) reported that under salinity stress, biochar restricts the ABA content in leaf and xylem sap of potato. When biochar is amended in saline soil with endophytic bacteria, it inhibits the ABA concentration in xylem of wheat and maize as compared to the unamended controls (Akhtar et al. 2015b, c). Stomatal conductance is known to be enhanced in plants grown in biochar-mediated soil under salt stress. Many recent studies (Thomas et al. 2013; Akhtar et al. 2015b, c) have revealed that biochar application to sodic/saline soils ameliorates the stomatal density and conductance in various herbaceous plants like wheat and tomato. Biochar not only improves soil properties but also enhances the soil moisture and sodium-binding capacity to biochar-amended soil which in turn reduces the root reactivity to osmotic stress (Akhtar et al. 2015c). Thus, the generation of ABA declines in the root which in turn enhances the stomatal conductance and leaf growth.

Salinity induces oxidative stress in plants by the excessive production of reactive oxygen species (Parihar et al. 2015; Farhangi-Abriz and Torabian 2017). Tartoura et al. (2014) showed that organic amendments lessen the salinity stress in plants by modulating the synthesis of antioxidant enzymes. A few studies reported that biochar mitigates the oxidative stress in plants grown in saline soils. Kim et al. (2016) found that maize under salinity stress generates high amount of ROS, but after amendment with biochar, the ascorbate peroxidase (APX) and glutathione reductase (GR) activities were declined as compared to control. Similarly, study by Lashari et al. (2015) revealed that compost of poultry manure plus diluted pyroligneous solution when applied on maize field under salt stress decreases MDA content in leaf sap. A very recent study (Farhangi-Abriz and Torabian 2017) reported

that biochar when amended in saline soil decreases the antioxidant enzyme activities of plants and releases the oxidative stress generated in bean seedlings. These studies formulated that biochar could improve plant growth and biomass under salt stress by reducing oxidative stress.

6.4.5 Effects on Plant Growth, Biomass, and Photosynthesis

Employment of biochar in salt-affected soils is proclaimed to augment the soil properties which in turn promote plant growth and photosynthesis. For example, biochar derived from wood, when amended in saline soil, enhanced the shoot biomass, tuber yield, and Pn in potato (Akhtar et al. 2015a). Another study by Kim et al. (2016) restores the tidal land (which contained high concentration of exchangeable sodium) with the help of biochar derived from rice hull, which further promotes the maize growth. Biochar addition enhances the tomato growth and biomass under saline condition (3.6 dS m^{-1}) (Usman et al. 2016). A study by Thomas et al. (2013) reported that biochar (pyrolyzed at 378 °C and applied at the rate of 50 t ha^{-1}) enhances the growth of two herbaceous plant (*Abutilon theophrasti* and *Prunella vulgaris*) under salt stress; however, photosynthetic carbon gains and chlorophyll fluorescence (Fv/Fm) value have not been affected by the presence of biochar.

Overall, the biochar response under salt stress varied from plant species to species. During salinity stress, biochar derived from compost when amended in soil could also promote the plant growth and biomass. For example, Lashari et al. (2013) reported that employment of biochar poultry manure compost (BPC) along with pyroligneous solution (PS) spray for 6 weeks in the saline soil enhanced the wheat grain production as compared to the control. In another study in maize field, BPC and PS treatments in salt-affected soil promote plant height, leaf area index, and photosynthetic pigments along with the increased grain yield (Lashari et al. 2015). However, when composted biochar was applied on two halophyte species under saline conditions, similar result was reported (Luo et al. 2017). During saline conditions, biochar application with the suitable microbial inoculants like plant growth-promoting rhizobacteria (PGPR) further improved the growth of plant as compared to the control and biochar-only treatments (Nadeem et al. 2013; Fazal and Bano 2016; Akhtar et al. 2015b, c). Another study by Hammer et al. (2015) found that arbuscular mycorrhizal (AM) fungi when incorporated with biochar under salinity stress showed increased growth of lettuce as compared to the treatments alone. The beneficial effect of biochar on ion homeostasis under salinity stress could be further enhanced by co-application of biochar with endophytic bacteria (Akhtar et al. 2015a, b). However, the combined application of wheat straw-derived biochar and P increased the phosphate precipitation/sorption in the saline–sodic soil and decreased P concentrations in plants (Xu et al. 2016). These studies illustrated that biochar might be very effective in mitigating salinity stress from the soil and also inhibits Na$^+$ uptake by plants grown in saline soils which in turn enhanced the mineral nutrients in plants. For example, the biochar and AM application promotes the P and Mn content in lettuce plants (Hammer et al. 2015). However, further research

is needed to establish the mechanisms of biochar-mediated mineral uptake by plants under saline conditions both at the soil and plant levels.

6.5 Effect on Soil Properties After Addition of Biochar

6.5.1 Modification of the Soil Habitat by Biochar

The material properties of biochar are very diverse from that of the uncharred organic matter in the soil (Schmidt and Noack 2000) and are evidently changed over a period of time due to weathering, interactions with soil mineral and organic matter, and oxidation by microorganisms in soil (Lehmann et al. 2005; Cheng et al. 2008; Cheng and Lehmann 2009; Nguyen et al. 2010). The mechanism of physical and chemical characteristics of biochar and its interaction with soil biota and microorganism are poorly understood.

6.5.1.1 Basic Properties: Organic and Inorganic Composition

Biochar composition can be divided into recalcitrant C, labile or leachable C, and ash. The major chemical difference between biochar and other organic matter is the much larger proportion of aromatic C and, specifically, the occurrence of fused aromatic C structures, in contrast to other aromatic structures of soil organic matter such as lignin (Schmidt and Noack 2000). The fused aromatic structure of biochars, when obtained at lower temperature, includes amorphous C, whereas when obtained at higher temperature, turbostratic C was formed (Keiluweit et al. 2010; Nguyen et al. 2010). The stability of biochar depends largely on these C structures (Nguyen et al. 2010). However, exact mechanism of the stability to the aromatic C structures in soil is not yet clear. The microbiota present in soil does not readily absorb the C (from the biochar) although a fraction of C may be leached and therefore mineralizable (Lehmann et al. 2009), and in some studies, it has been shown that biochar stimulates the microbial activity and hence abundance (Steiner et al. 2008). At present, such fractions may be quantified by incubation studies and are frequently referred to as "volatile matter" or the labile fraction. Volatile matter refers to an ASTM standard methodology that was developed to evaluate the quality of coals as fuels and determine the stability of biochar (Deenik et al. 2010; Zimmerman 2010). However, such quantified volatile matter (5–37% of C in the study by Zimmerman 2010) is typically much larger than the corresponding mineralization (2–18% of C over 1 year). This may indicate that the mineralizable fraction is imperfectly captured by volatile matter. The next main component consists of minerals present as ash inclusions in biochar. These minerals include several significant macro- and micronutrients for biological absorption and thus the concept of valuable resources in the soil food chain. The presence of these elements during pyrolysis stimulates organo-metal reactions which are thermodynamically favorable at high temperatures. For example, N may replace one or two C atoms in aromatic compounds (Leinweber et al. 2007) with largely unknown effects on biochar behavior in soil. Iron (Fe)-rich biochars made from peat and investigated by ^{57}Fe Mossbauer

spectroscopy show the formation of Fe_3C bonds and small ferromagnetic iron clusters at pyrolysis temperatures over 600 °C (Freitas et al. 2002). Grass and a variety of common raw materials (rice shells, sludge from purification plants, etc.) also contain significant amounts of amorphous silica (>2 wt%). The Si-C bonds usually participate in cross-links between aromatic domains and crystallites (Freitas et al. 2000). At temperatures of 400–600 °C, pyrolysis alters the chemical structure of biosilicates, with a continuous increase of SiO_4 relative to $SiO_{2–3}$ with increasing heat treatment temperature (Freitas et al. 2000). Silicates can absorb a significant proportion (>14% for corn cobs and 88% for rice shells) of biochar pore volume (Bourke et al. 2007; Freitas et al. 2000).

## 6.5.2 Responses of the Soil Biota to Biochar

The use of biochar as a targeted strategy for controlling soil biota is an issue of increasing interest, and unintended changes to the soil's biota as a result of biochar application are of the same concern. This line of research is important as the health and diversity of soil microbial populations are crucial for soil functional and ecosystem services, which in turn affect the soil structure and stability, nutrient cycle, aeration, water utilization efficiency, disease resistance, and C storage capacity (Brussaard 1997). Incorporation of various organic matters to the soil is one of the most important means of managing biodiversity in soils (Brussaard et al. 2007). The distributions of organic amendments, quantity, and quality affect the trophic structure of the soil food web (Moore et al. 2004). Therefore, all three of these aspects should be considered in the use of biochar as a soil management tool. In the following section, we discuss how the biochar affects the:

 I. Growth of microorganism
II. Nutrient transformation

In the following sections, we consider how biochar affects soil biota on several trophic levels, including root dynamics, and discuss the reasons behind observed changes with respect to different biochar properties.

6.5.3 Abundance of Microorganisms

Microbial abundance has been assured in biochar-amended soil by various methods like total genomic DNA extraction (Jin 2010), culturing and plate counting (Jackson 1958), substrate-induced respiration (Steiner et al. 2004; Kolb et al. 2009), fumigation extraction (Jin 2010; Liang et al. 2010), phospholipid fatty acid (PLFA) extraction (Birk et al. 2009), staining, and direct observation of individual biochar particles (Jackson 1958; Pietikäinen et al. 2000; Warnock et al. 2007; Jin 2010; Fig. 6.2). The microbial reproduction rate has been uplifted in some biochar-amended soils (Steiner et al. 2004) and in wastewater (Koch et al. 1991). In case of bio-digesters
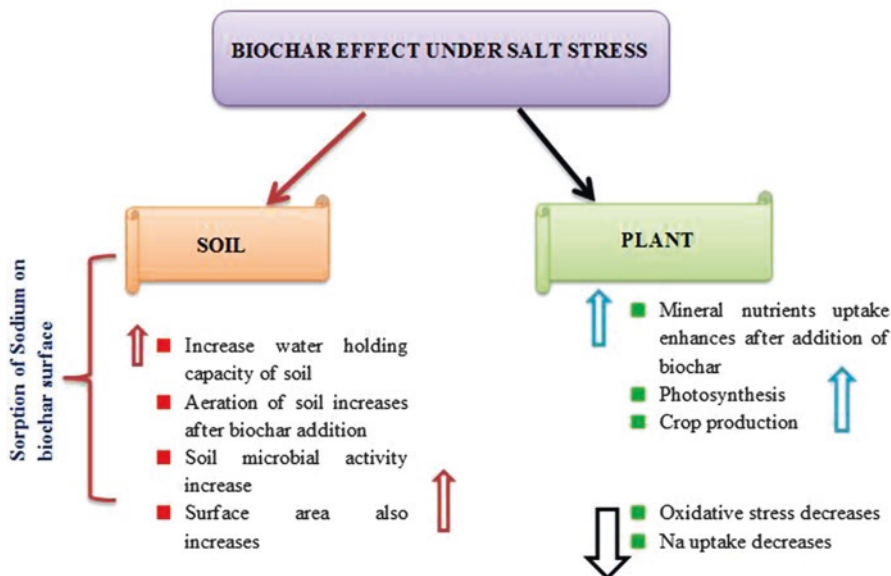
Fig. 6.2 Biochar effects under salt stress

which are used to evolve methane (CH_4) (as an energy source) after the addition of biochar led to an increase in anaerobic and cellulose-hydrolyzing bacteria (Kumar et al. 1987). The changes in microbial abundance vary within the groups of microorganism. In case of mycorrhizal fungi (arbuscular and ectomycorrhizal), enhanced growth was observed (Warnock et al. 2007). Mycorrhizal response in the host plant is most commonly measured by measuring the root colonization. Both formation rate and tip number of EM infection of larch seedling roots were increased by 19–157% with biochar additions (Makoto et al. 2010). Likewise, AM colonization of wheat roots was found to increase to 20–40% 2 years after *Eucalyptus* wood biochar additions of 0.6–6 t ha^{-1}, in comparison to a colonization rate of 5–20% in unamended controls (Solaiman et al. 2010). Biochar derived through hydrothermal carbonization stimulates the spore germination of AM fungi, which further enhances the populations of these symbionts in the soil (Rillig et al. 2010). Although, some studies (Gaur and Adholeya 2000; Birk et al. 2009; Warnock et al. 2010) revealed that after biochar addition AM abundance decreases. The reasons behind the decline in population are still not clear; however, it could be because of (1) a reduced requirement for mycorrhizal symbiosis due to increased in nutrient and water availability to plants which cause decreases in mycorrhizal abundance, for example, with greater P availability in soil (Gryndler et al. 2006); (2) changes in soil conditions, e.g., due to modifications of pH or water relations (discussed below); (3) direct negative effects from high contents of mineral elements or organic compounds detrimental to the fungi, such as high salt or heavy metal contents (Killham and Firestone 1984; Killham 1985); and (iv) sorption of organic C and organically

bound nutrients may influence their availability (Pietikäinen et al. 2000; Chan and Xu 2009).

The nutrient and C availability change the increase or decrease in microbial biomass, depending on (1) the existing nutrient and C availability in soil, (2) the magnitude of change, and (3) the microorganism group (Warnock et al. 2010). Bacteria may sorb to biochar surfaces and make them less susceptible to leaching in soil (Pietikäinen et al. 2000). Thus, it increases bacterial abundance although it has no effect on fungal abundance. The ability of biochars to retain bacteria will vary greatly depending on the biochar properties including the ash content, pore size, and volatile content that are highly variable (Bond 2010). Formation of surfactants by microorganisms (Ron and Rosenberg 2001) may additionally facilitate adhesion to biochars.

6.5.4   Effect of Biochar on Nutrient Transformation

Biochar can have influential effects on microbially mediated transformation of nutrients in soil. In forest soils, nitrification has been enhanced after the amelioration of soil with the biochar (MacKenzie and DeLuca 2006; Ball et al. 2010) which in turn increases sorption of phenolic that would otherwise inhibit nitrification (Zackrisson et al. 1996; DeLuca et al. 2006) and an increase in ammonia-oxidizing bacteria (Ball et al. 2010). However, biochar additions to agricultural soil show no change in net N mineralization (DeLuca et al. 2006) and less N availability to the plants (Lehmann et al. 2003). The higher the mineralizable fraction of biochar (often quantified and described as volatile matter), the greater the N immobilization with resultant decreases in N uptake and growth of crops (Deenik et al. 2010). A high microbial biomass content was observed after biochar additions. An enhanced activity of alkaline phosphatase, aminopeptidase, and N-acetylglucosaminidase was found to increase with biochar applications (Bailey et al. 2010; Jin 2010). Alkaline phosphatase increased by 615% and aminopeptidase by 15% with increasing rates of corn biochar application to an alfisol (Jin 2010). Biochar triggers the growth of fine roots and root hairs which in turn raised the production of organic N and P mineralization enzymes (Bailey et al. 2010). Biochar induces changes in the bacterial community similar to rhizosphere effects.

6.5.5   Biochar and Plant Roots

Various studies (Breazeale 1906; Nutman 1952) showed that the biochar materials have been reported to stimulate the root growth (Breazeale 1906; Nutman 1952). The different properties of biochar in comparison to the soil cause the improved root growth; however, roots may grow into the biochar pores (Lehmann et al. 2003; Joseph et al. 2010). After forest fire, a layer of char enhances the root biomass (47%) and also root tip number (64%) (Makoto et al. 2010). The root length of rice was also increased with biochar additions (Noguera et al. 2010). Germination and

rooting of fir embryos (*Abies numidica*) significantly increased from 10% to 20% without additions to 32–80% of embryos when activated carbon was added to various growth media (Vookova and Kormutak 2001). Therefore, not only abundance but also growth behavior of roots may change in response to the presence of biochar. When the soils are amended with biochar, it improves the physicochemical properties of the soil like water availability, pH, and aeration which likely enhance root growth and also enhance shoot to root ratio (Wilson 1988). A study by Breazeale (1906) and Dachnowski (1908) have illustrated the pronounced increase in root growth after additions of carbon black (soot) to soil with sorption of allelopathic compounds that were phytotoxic. Inderjit and Callaway (2003) found that activated carbon neutralizes the phytotoxic compounds present in soil. Although these results have been challenged by Lau et al. (2008), they revealed that nutrients leaching from the activated carbons and that the addition of carbonaceous adsorbents may have multiple effects on soil. No studies have been published which showed the toxic effect of biochar on plant growth, i.e., plant growth decreased while shoot to root ratio increased.

6.6 Conclusion and Future Perspectives

Crop growth and yields have seriously been affected due to salt stress. Studies reported that the biochar application enhances the plant growth and biomass during salt stress. Biochar when applied in soil enhances photosynthesis and nutritional uptake and modified gas exchange properties in plants. Biochar inhibits Na^+ uptake while increased K^+ uptake in salt-stressed plants. The biochar amelioration increases the capability of the plant to tolerate high salt condition by the reduction of Na^+ uptake, accumulation of minerals, and regulation of stomatal conductance and plant hormones. Overall, this chapter develops a better understanding of the biochar-mediated tolerance mechanisms in plants under salt stress. However, more research is needed to establish a different mechanism for biochar-mediated mineral uptake at plant and soil. The effect of biochar on soil also depends on the type of biochar (raw material), pyrolysis temperature, and the type of soil.

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