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REVIEW

Free radical scavenging and antioxidant potential of mangrove plants: a review

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Abstract Free radicals derived from reactive oxygen species and reactive nitrogen species are generated in our body by normal cellular metabolism which is enhanced under stress conditions. The most vulnerable biological targets of free radicals are cell structures including proteins, lipids and nucleic acids. Since antioxidants synthesized in the body are not sufficient under oxidative stress, their exogenous supply is important to prevent the body from free radical-induced injury. Recent researches have shown that antioxidants of plant origin with free radical scavenging property could have great importance as therapeutic agents in management of oxidative stress. Mangrove plants growing in inhospitable environment of the intertidal regions of land and sea in tropics and sub-tropics are equipped with very efficient free radical scavenging system to withstand the variety of stress conditions. These mangrove plants possess variety of phytochemical and are rich in phenolic compounds such as flavonoids, isoflavones, flavones, anthocyanins, coumarins, lignans, catechins, isocatechins, etc., which served as source of antioxidants. Isolation and identification of these antioxidant compounds offer great potential for their pharmaceutical exploitations. However, no comprehensive literature is available on antioxidants' studies in mangrove plants in particular. Hence, the present review discusses the antioxidant potential of mangrove plants with its specific role under salt stress as well as the progress made so far in evaluation of antioxidant activities of different mangrove species.

Keywords Free radicals · Reactive oxygen species · Oxidative stress · Salt stress · Antioxidants in mangroves

Introduction

Free radicals or oxidative injury now appears to be the consequence of a number of human disorders and diseases. When a reactive molecule such as reactive oxygen, reactive nitrogen and reactive chlorine species contains one or more unpaired electrons, the molecule is termed as a free radical (Chanda and Dave 2009). Several free radicals [superoxide radical ($O_2^{\cdot-}$), hydroxyl radical (OH·), perhydroxyl radical (HO_2·), alkoxy radicals (RO·), nitric oxide (NO·)] and non-radicals [hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), hydrochlorous acid (HOCl), nitrous oxide (HNO_2), alkyl peroxynitrates (RONOO)] are produced during normal physiological processes in the plant as well as animal system. The free radical superoxide is generated from O_2 by multiple pathways and further triggers the generation of more reactive ROS such as OH·, $^1O_2$, etc. (Halliwell 2006). Singlet oxygen, which is normally associated with chlorophyll pigment of plants, is found to have powerful damaging effect on PSI and PSII as well as on the whole photosynthetic machinery which may trigger cell death (Wagner et al. 2004). Hydrogen peroxide, a non-radical is produced through two-electron reduction of O_2 by cytochrome P-450, D-amino acid oxidase, acetyl coenzyme A oxidase, or uric acid oxidase (Asada et al. 1974). Hydrogen peroxide and superoxide radical by themselves are relatively less damaging. However, they can form species such

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as hydroxyl radicals that can initiate lipid peroxidation and also attack DNA, proteins and many small molecules (Asada 2006). Similarly, peroxynitrite ($ONOO^-$), a potent cytotoxic free radical is found to be produced by the reaction of nitric oxide and superoxide ion in oxidative stress conditions.

Free radicals are generated from exogenous and endogenous sources. The exogenous sources include mainly environmental radiations and man-made sources whereas various endogenous sources encompass physiological activities such as respiration, phagocytosis, intoxication and fatty acid metabolism (Krishnaiah et al. 2007). In plants, ROS formation always occurs during normal growth and metabolism, particularly in sub-cellular locations with high-enzymatic redox turnover. It has been estimated that 1–2 % of O_2 consumed by plants is side tracked to produce ROS in various sub-cellular loci such as mitochondria, chloroplasts or peroxisomes (Bhattacharjee 2005). To counteract these oxidative stress plants produce potent antioxidants that include both enzymatic and non-enzymatic antioxidant system (Asada 2006). Plant-derived antioxidants have been shown to function as singlet and triplet oxygen quenchers, free radical scavengers, peroxide decomposers, enzyme inhibitors, and synergists (Salekdeh et al. 2002).

It is found that production of reactive oxygen species (ROS) in plants is enhanced under stress conditions such as low temperature, salt, drought, heat, oxidative stress and heavy metal toxicity. These stress factors are accentuated by various anthropogenic activities (Mahajan and Tuteja 2005). Stress-induced ROS accumulation is counteracted by enzymatic antioxidant systems of the plant that include a variety of scavengers, such as super oxide dismutase (SOD), ascorbate peroxidase (APX), glutathione peroxidase (GPX), glutathione reductase (GR), dehydroascorbate reductase (DHAR) and catalase (CAT), and non-enzymatic low molecular metabolites such as reduced glutathione (GSH), ascorbic acid (vitamin C), α-tocopherol (vitamin E), carotenoids and flavonoids (Gill et al. 2011). However, the equilibrium between the production and the scavenging of ROS may be perturbed by various biotic and abiotic stress factors such as salinity, UV radiation, drought, heavy metals, temperature extremes, nutrient deficiency, air pollution, herbicides and pathogen attacks (Mittler et al. 2004).

Unlike terrestrial plants, mangrove plants growing in saline habitats need special mention here because of their ability to survive under stress conditions such as high salinity, extreme tides, strong winds, high temperature and anaerobic soil. To neutralize the ROS generated due to exposure of stressful conditions, mangrove plants produce high concentration of the antioxidant enzymes (Das et al. 2001). Evaluation of bioactive compounds reveals that the mangrove plants are rich in phenolic compounds such as flavonoids, isoflavones, flavones, anthocyanins, coumarins, lignans, catechins and isocatechins which served as source of antioxidants (Bandaranayake 2002; Schwarzländer et al. 2008).

In recent years, mangrove plants have attracted much of our attention because of their rich antioxidant system which has much therapeutic values for a number of diseases such as neurodegenerative disorders, inflammation, viral infections, autoimmune pathologies and digestive system disorders that require external source of antioxidants to fight with excess production of free radicals in the human body (Bandaranayake 1998; Ramchoun et al. 2009). The antioxidants from plants in general and mangroves in particular in the form of herbal drugs play an important role to protect the body from free radical-induced injury, and thus, present a great scope for their pharmaceutical application. The present review reports free radical scavenging and antioxidant defense mechanism in mangrove plants, correlation between antioxidant enzymes with salinity stress and the progress made so far on studies related to antioxidant activities of mangrove plants, as rich source for many biologically active compounds.

Antioxidant defense mechanisms in mangrove plants

Mangroves are salt tolerant plant communities occurring in intertidal regions between land and sea in tropical and subtropical regions of the world. These regions are ecologically unstable and stressful environment. A limited number of plant communities comprise of trees, shrubs and herbs are capable of surviving in these hostile environmental conditions as exemplified by water logging, high salinity, low oxygen, high wind and high temperature (Kathiresan and Bingham 2001). About 80 species of mangrove plants are known worldwide. The important genera of mangrove plant comprise *Acanthus*, *Avicennia*, *Aegiceras*, *Exocariaceae*, *Rhizophora*, *Kandelia*, *Ceriops*, *Bruguiera*, *Xylocarpus*, *Sonneratia*, *Suaeda*, which encompass more than one species each. These mangroves represent a unique plant community possessing an adaptive capability in terms of morphological, anatomical, physiological and molecular mechanisms to cope of with various environmental stresses (Dasgupta et al. 2010). Environmental stresses such as high-light intensity, temperature extremes, drought, high salinity, low oxygen induce oxidative stress in mangrove plants through an enhanced generation of ROS (Jithesh et al. 2006a; Kathiresan and Bingham 2001). Mangrove plant cells are well protected against these detrimental effects of ROS by a complex antioxidant system comprising non-enzymatic and enzymatic antioxidants (Kathiresan and Bingham 2001). Antioxidants in mangrove

plants can be categorized into two broad classes such as preventive antioxidants and chain breaking antioxidants (Gill and Tuteja 2010). The preventive antioxidants inhibit oxidation reaction by reducing the rate of chain initiation whereas commercial chain breaking antioxidants inhibit oxidation reaction by trapping peroxyl radicals (Arora et al. 2002). The components of antioxidant defense system of mangrove plants can be categorized into four different types: (1) enzymatic antioxidants, (2) non-enzymatic antioxidants, (3) nutrient antioxidants, metal-binding proteins like ferritin, and (4) phytoconstituents and phytonutrients (Mittler 2002).

Enzymatic antioxidants

The enzymatic defense system of mangrove plants include different endogenous enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPX), glutathione reductase (GR), etc.

Superoxide dismutase (SOD)

Metalloenzyme SOD is the most effective intracellular enzymatic antioxidant and acts as a first-line defense against ROS-mediated oxidative stress. It catalyzes the disproportionation of superoxide to molecular oxygen and H_2O_2 (Scandalios 1993). Three isozymes of SOD namely Mn-SOD, Cu/Zn-SOD and Fe-SOD on the basis of the metal cofactor have been reported in various plant species which are localized in different cellular compartments (Mittler 2002). Increase in activity of thylakoid bound SOD, Mn-SOD and Fe-SOD was observed under salinity stress in *Suaeda salsa* (Fang et al. 2005). Steep increase in total SOD activity levels has been recorded in *Bruguiera gymnorrhiza* and *B. parviflora* during salt stress (Takemura et al. 2000; Parida et al. 2004). It has been reported that the SOD activities in field-grown mangrove *Rhizophora stylosa* were more than 40 times that of peas (Cheeseman et al. 1997).

Catalase and peroxidases (POX)

Catalase and peroxidases are the most important enzymes that regulate the intracellular level of H_2O_2 (Willekens et al. 1995). In another study, a class II enzyme, Cat1 from *A. marina*, was reported to be induced upon salt and other oxidative stress, such as exposure to H_2O_2 and light, in leaves (Takemura et al. 2002; Jithesh et al. 2006a). Similarly, catalase activity was found to be increased under salt stress in mangrove *B. gymnorrhiza* (Takemura et al. 2000). However, decrease in catalase activity was observed in *B. parviflora*, *Crithmum maritimum* and *S. nudiflora* under salt stress (Takemura et al. 2000; Parida et al. 2004; Ben Amor et al. 2005).

Mangrove plants contain abundant amounts of peroxidases (POX) that are involved in H_2O_2 scavenging. Cherian et al. (1999) have reported the increased POX activity in root and shoot tissues in *Avicennia marina* under NaCl stress conditions. Ascorbate peroxidase (APX) is thought to play the most essential role in scavenging ROS and protecting cells in higher plants and other organisms (Noctor and Foyer 1998). Parida et al. (2004) have reported increase in APX content in *Bruguiera parviflora* under salt stress.

Glutathione and glutathione reductase (GR)

Glutathione, glutamyl cysteinyl glycine (GSH) plays a central role in several physiological processes, including regulation of sulfate transport, signal transduction, conjugation of metabolites, detoxification of xenobiotics (Xiang et al. 2001) and the expression of stress-responsive genes (Mullineaux and Rausch 2005). Huang et al. (2010) reported increase in GSH level in response to ROS generated through heavy metal stress in *K. candel*.

Non-enzymatic antioxidants

To control the level of ROS and to protect cells under stress conditions, mangrove plant tissues have well-developed network of low molecular mass non-enzymatic antioxidants viz. ascorbate, tocopherols and phenolic compounds (Jithesh et al. 2006a). High concentration of ascorbate was observed in whole leaves of *Rhizophora stylosa* under oxidative stress, suggesting its important role in scavenging superoxide radicals in mangroves (Cheeseman et al. 1997). Parida et al. (2004) have reported reduction in ascorbic acid and glutathione levels in the mangrove plant *B. parviflora* during salt stress.

α-Tocopherols (vitamin E)

Tocopherols, lipid-soluble antioxidant, are considered as potential scavengers of ROS and lipid radicals (Hollander-Czytko et al. 2005). The role for α-tocopherol in scavenging of superoxide radicals in mangroves during oxidative stress conditions was reported (Cheeseman et al. 1997).

Phenolic compounds

Phenolics characterize a diverse group of compounds comprised of flavonoids, tannins, lignins, coumarins, etc. These compounds possess ideal structural features for

showing free radical scavenging property and found as effective as ascorbate and tocopherols. The antioxidant properties of these mangrove plants are attributed due to the presence of high amount of phenolic compounds viz. flavonoids and their derivatives, terpenoids, phytoalexins, coumarin derivatives, tannin and its derivatives (Banerjee et al. 2008; Patra et al. 2011).

Nutrient antioxidants, metal-binding proteins

Nutrient-derived antioxidants such as ascorbic acid (vitamin C), tocopherols and tocotrienols, carotenoids, and other low molecular weight compounds such as glutathione and lipoic acid play significant role in neutralizing the oxidative stress. Metal-binding proteins such as ferritin, lactoferrin, albumin, and ceruloplasmin that sequester free iron and copper ions are capable of catalyzing oxidative reactions. In addition to enzymatic detoxification of ROS, controlling the concentration of free transition metals like iron plays an important role in prevention of oxidative damage as iron promotes hydroxyl radical formation through Fenton's reaction (Lobreaux et al. 1995). To counteract the deleterious effect of accumulation iron, plants have produced specific protein molecules like ferritin to overcome the problem of biological insolubility and potential toxicity of iron in the presence of oxygen. The ferritin is a multimeric protein that participates in the protection of plastids by sequestering several thousand iron atoms in their central cavity (Theil 1987; Harrison and Arosio 1996). Ferritin was shown to be an important constituent of the oxidative stress response in halophytes and participates in the defense of chloroplasts against oxidative stress (Paramonova et al. 2004). This was further supported by studies carried out by Jithesh et al. (2006b) on *A. marina* in which *Fer1* (the gene responsible for expression of protein ferritin) mRNA levels were found to be up-regulated under metal, salt and oxidative stress (Jithesh et al. 2006b).

Phytoconstituents and phytonutrients

Mangrove plant-derived substances, collectively termed "phytonutrients", or "phytochemicals", are becoming increasingly known for their antioxidant activity. Phenolic compounds such as flavonoids serve as protectors against a wide variety of environmental stresses in plants. Other phytoconstituents like alkaloids from mangroves found to be potent inhibitors of various oxidative processes (Bandaranayake 2002). The five carbon building units are synonymously termed as terpenoids, terpenes or isoterpenoids. The triterpenoids are the most common terpenes in plants and found to possess protective function against oxidative damage (Bandaranayake 2002). Other phytoconstituents such as sugars, polyols, amino acids, and tertiary and quaternary ammonium compounds are osmoprotectants synthesized in response to stress protect the cellular structure of the plant in various stress conditions (Rhodes and Hanson 1993). Glycine betaine (GB), a quaternary ammonium compound, is found to play a critical role in protection of thylakoid membranes and in maintaining photosynthetic machinery in *S. maritima* (Genard et al. 1991). Similarly, proline is one of the most prominent osmolytes in plant and stabilizes sub-cellular structures, scavenges free radicals and maintains the cellular redox potential under stress conditions. Increased proline content in mangrove plant *S. nudiflora* with decreased ROS production under salt stress has been observed by Cherian and Reddy (2003). In mangrove plants, proline also scavenges singlet oxygen and free radical-induced damages and performs an important role in protection of proteins against denaturation (Alia et al. 1991).

Methods for evaluation of antioxidant properties in mangrove plants

The simplest way to test the ability of an antioxidant is to directly expose the antioxidant to ROS sources such as UV light, metal ions, $^1O_2$, $OONO^-$, etc. The interactions between antioxidants and radicals give direct evidence of the ability of antioxidants to trap radicals. Thus, if some stable radicals or some methods to generate radicals readily are available in a laboratory, the radical scavenging property of the synthesized or extracted compounds can be explored promptly. Recently, the capacity of antioxidants for scavenging free radicals has been assessed more often and widely by either the reaction with stable reference radical or by competition methods using conventional UV/Visible absorption spectrophotometer (Ksouri et al. 2009; Pandhair and Sekhon 2006). Different terms such as ability, activity, capacity, efficacy, parameter, potential, power and reactivity have been used to express the free radical scavenging capacity of antioxidants. The free radical scavenging capacity of antioxidants in vitro has been evaluated by several different methods under different conditions. The capacity of antioxidant compound for scavenging free radicals is assessed by two factors, i.e., rate of scavenging radicals and number of radicals each antioxidant molecule can scavenge, which are determined inherently by the chemical structure of the antioxidant compound and also the free radicals (Ksouri et al. 2009). Different screening methods are available for evaluation of antioxidant properties of the plant extracts. The most commonly used ones are those involving chromogen compounds of radical

nature that stimulate the reductive oxygen species. The presence of antioxidants leads to the disappearance of these radical chromogens; the most widely used ones being the ABTS (2,2′-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid), nitric oxide scavenging assay and DPPH (2,2-diphenyl-1-picrylhydrazyl) methods. Some other commonly used assays such as FRAP (ferric reducing antioxidant power) assay, ORAC (oxygen radical absorption capacity) assay, etc. are described in Table 1 that gives information about various mechanisms involved in various in vitro antioxidant assay methods (Ksouri et al. 2009; Pandhair and Sekhon 2006). Several methods have been applied for the assessment of free radical scavenging capacity of mangrove plants. DPPH free radical scavenging assay is the most widely reported method for screening of antioxidant activity of many plant drugs. DPPH assay method is based on the reduction of methanolic solution of colored free radical, DPPH by free radical scavenger in the presence of a hydrogen-donating antioxidant due to the formation of the non-radical form, DPPH-H. The procedure involves measurement of decrease in absorbance of DPPH at its absorption maxima of 516 nm, which is proportional to concentration of free radical scavenger added to DPPH reagent solution (Chanda and Dave 2009; Patra et al. 2008). The in vitro inhibition of nitric oxide radical is also a measure of antioxidant activity which is based on the inhibition of nitric oxide radical generated from sodium nitroprusside at physiological pH interacts with oxygen to produce nitrite ions, which were measured using the Griess reaction reagent (Chanda and Dave 2009). The "total antioxidant capacity" (TAC) assay is based on the reduction of Mo(IV) to Mo(V) by the extract and subsequent formation of a green phosphate/Mo(V) complex at acid pH (Ksouri et al. 2009; Prieto et al. 1999). The amount of total phenol content can be determined by Folin–Ciocalteu reagent method (McDonald et al. 2001). Iron is essential for life because it is required for oxygen transport, respiration and activity of many enzymes. However, iron is an extremely reactive metal and catalyzes oxidative changes in lipids, proteins and other cellular components. It causes lipid peroxidation through the Fenton and Haber–Weiss reaction (Halliwell 2006) and decomposes the lipid hydroxide into peroxyl and alkoxyl radicals that can perpetuate the chain reactions (Halliwell 2006). In the metal chelating assay, ferrozine can quantitatively chelate with Fe^{2+} and form a complex with a red color. This reaction is limited in the presence of other chelating agents and results in a decrease of the red color of the ferrozine–Fe^{2+} complexes. Measurement of the color reduction estimates the chelating activity to compete with ferrozine for the ferrous ions (Soler-Rivas et al. 2000). Reducing power is associated with antioxidant activity and may serve as a significant reflection of the antioxidant activity (Oktay et al. 2003). Compounds with reducing power indicate that they are electron donors and can reduce the oxidized intermediates of lipid peroxidation processes, so that they can act as primary and secondary antioxidants (Yen and Chen 1995). The reducing power can be determined by the method of Athukorala et al. (2006). The FRAP (ferric reducing antioxidant power) method relies on the reduction by the antioxidants, of the complex ferric ion-TPTZ [2,4,6-tri (2-pyridyl)-1,3,5-triazine] (Thaipong et al. 2006). The ORAC (oxygen radical absorption capacity) method measures the antioxidant scavenging activity against the peroxyl radical, induced by 2,2′-azobis-(2-amidino-propane)dihydrochloride (AAPH) (Denev et al. 2010). The HORAC technique relies on the measurement of the metal-chelating activity of antioxidants, under the conditions of Fenton-like reactions. The method uses a Co(II) complex and hence evaluates the protecting ability against the formation of hydroxyl radical (Pisoschi and Negulescu 2011). Similarly, the phosphomolybdenum assay is used for determining the antioxidant capacity based on the reduction of Mo(VI)–Mo(V) by the antioxidants and subsequent formation of a green phosphate/Mo(V) complex at acid pH (Selvakumar et al. 2011). TLC screening method can also be used for biological testing for discovering new antioxidants in higher plants. These can be detected on a TLC plate by spraying with 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical. Antioxidants reduce the radical, producing white spots on a purple background. Alternatively, the bleaching of crocin (which normally gives a yellow color on the plate) can be used to distinguish components of plant extracts with potential antioxidant or radical scavenging properties (Cuendet et al. 1997).

Correlation between antioxidants and salinity stress in mangroves

Mangroves inhabiting ecologically challenging intertidal zones are subjected to various abiotic stresses because of unfavorable environmental conditions which adversely affect their growth and development and trigger a series of morphological, physiological, biochemical and molecular changes (Dasgupta et al. 2010). These abiotic stresses encompass drought, salinity, extreme temperature, chemical toxicity, hypoxia, ultraviolet radiation, nutrition deficiency, etc. that culminated into enhanced production of ROS. Mangroves with high levels of antioxidants, either constitutive or induced, have been reported to have greater resistance to this oxidative damage (Jithesh et al. 2006a; Takemura et al. 2000; Parida et al. 2004; Cheeseman et al. 1997). Halophytes known for their unique ability to tolerate high salinity are studied to elucidate the mechanism underlying their capacity to handle high salt concentration.

Table 1 Different methods and their mechanism of action for determination of antioxidant properties in mangrove plants

S. no.	Method	Mechanism	References
1.	Total antioxidant capacity (TAC)	The TAC assay is based on the reduction of Mo(IV) to Mo(V) by the extract and subsequent formation of a green phosphate/Mo(V) complex at acid pH	Serafini and Del Rio (2004), Ksouri et al. (2009), Prieto et al. (1999)
2.	Total phenol content	Folin–Ciocalteu reagent method	McDonald et al. (2001)
3.	Total flavonoids content	Total flavonoids were measured by a colorimetric assay	Ali et al. (2008)
4.	Total carotenoids content	Total carotenoids content was determined by the spectrophotometric method at 470 nm, using a β-carotene (0.001–0.005 mg/mL) standard curve.	Ali et al. (2008)
5.	DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay	DPPH assay method is based on the reduction of methanolic solution of colored free radical, DPPH by free radical scavenger in the presence of a hydrogen–donating antioxidant due to the formation of the non-radical form, DPPH-H. The procedure involves measurement of decrease in absorbance of DPPH at its absorption maxima of 516 nm, which is proportional to concentration of free radical scavenger added to DPPH reagent solution	Chanda and Dave (2009), Patra et al. 2008
6.	Nitric oxide scavenging assay	This method is based on the inhibition of nitric oxide radical generated from sodium nitroprusside at physiological pH interacts with oxygen to produce nitrite ions, which were measured using the Griess reaction reagent	Chanda and Dave (2009)
7.	Metal chelating assay	In the metal chelating assay, ferrozine can quantitatively chelate with Fe^{2+} and form a complex with a red color. This reaction is limited in the presence of other chelating agents and results in a decrease of the red color of the ferrozine-Fe^{2+} complexes. Measurement of the color reduction estimates the chelating activity to compete with ferrozine for the ferrous ions	Soler-Rivas et al. (2000)
8.	Reducing powder	Compounds with reducing power indicate that they are electron donors and can reduce the oxidized intermediates of lipid peroxidation processes, so that they can act as primary and secondary antioxidants.	Yen and Chen (1995), Athukorala et al. (2006)
9.	Hydrogen peroxide scavenging activity	The principle of this method is that there is a decrease in absorbance of H_2O_2 upon oxidation of H_2O_2	Mallik et al. (2011)
10.	ABTS (2,2′-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid) radical scavenging assay	The ABTS cation radical (ABTS·+) which absorbs at 743 nm (giving a bluish-green color) is formed by the loss of an electron by the nitrogen atom of ABTS. In the presence of Trolox (or of another hydrogen-donating antioxidant), the nitrogen atom quenches the hydrogen atom, yielding the solution decolorization.	Thaipong et al. (2006), Pisoschi and Negulescu (2011)
11.	The FRAP (ferric reducing antioxidant power) method	The FRAP (ferric reducing antioxidant power) method relies on the reduction by the antioxidants, of the complex ferric ion-TPTZ (2,4,6-tri(2-pyridyl)-1,3,5-triazine)	Thaipong et al. (2006), Pisoschi and Negulescu (2011), Pellegrini et al. (2003)
12.	The ORAC (oxygen radical absorption capacity) assay:	The ORAC method measures the antioxidant scavenging activity against the peroxyl radical, induced by 2,2′-azobis-(2-amidino-propane) dihydrochloride (AAPH), at 37 °C.	Thaipong et al. (2006), Denev et al. (2010)
13.	The HORAC (hydroxyl radical averting capacity) assay:	The HORAC technique relies on the measurement of the metal-chelating activity of antioxidants, under the conditions of Fenton-like reactions. The method uses a Co(II) complex and hence evaluates the protecting ability against the formation of hydroxyl radical.	Pisoschi and Negulescu (2011), Denev et al. (2010)
14.	The TRAP (total peroxyl radical trapping antioxidant parameter) assay	The TRAP assay is based on the luminol-enhanced chemiluminescence (CL) was exploited to monitor the reactions involving the peroxyl radical. The CL signal is driven by the production of luminol derived radicals, resulted from the thermal decomposition of AAPH.	Cízová et al. (2004), Pisoschi and Negulescu (2011)

Table 1 continued

S. no.	Method	Mechanism	References
15.	The lipid peroxidation inhibition assay	The lipid peroxidation inhibition assay method uses a Fenton-like system (Co(II) + H_2O_2), to induce lipid (e.g., fatty acid) peroxidation	Slavíková et al. (1998), Pisoschi and Negulescu (2011)
16.	The CUPRAC (cupric reducing antioxidant power) assay	In the CUPRAC assay, Cu(II) is reduced to Cu(I) through the action of electron-donating antioxidants	Apak et al. (2004), Thaipong et al. (2006)
17.	Phosphomolybdenum assay:	The phosphomolybdenum assay used for determining the antioxidant capacity is based on the reduction of Mo(VI)–Mo(V) by the antioxidants and subsequent formation of a green phosphate/Mo(V) complex at acid pH.	Selvakumar et al. (2011)
18.	Superoxide anion radical scavenging activity	The photochemically reduced riboflavin generated $O_2{\cdot}-$ which reduced NBT to form blue formazan	Mallik et al. (2011)
19.	Glutathione-S-transferase Activity	GST activities were determined spectrophotometrically by monitoring the thioester formation at 340 nm using 1-chloro-2,4-dinitrobenzene (CDNB) as the substrate	Patra et al. (2008)
20.	Fluorimetry	Fluorescence emission occurs when an orbital electron of a molecule relaxes to its ground state, by emitting a photon of light after being excited to a higher quantum state by some type of energy. Fluorescence assay has been used to antioxidant content determination.	Chong and Olsher (2007)
21.	Dichlorofluorescin-diacetate (DCFH-DA)-based assay	This assay uses AAPH to generate peroxyl radicals and DCFH-DA as the oxidizable substrate for the peroxyl radicals. The oxidation of DCFH-DA by peroxyl radicals converts DCFH-DA to dichlorofluorescein (DCF). DCF is highly fluorescent (Ex 480 nm, Em 526 nm) and also has absorbance at 504 nm. Therefore, the produced DCF can be monitored either fluorometrically or spectrophotometrically.	Amado et al. (2007)
22.	Photochemiluminescence (PCL) assay	The photochemiluminescence measures the antioxidant capacity, towards the superoxide radical, in lipidic (ACL) and water (ACW) phase. This method allows the quantification of both the antioxidant capacity of hydrophilic and/or lipophilic substances, either as pure compounds of complex matrix from different origin: synthetic, vegetable, animal, human, etc.	Popov and Lewin (1996)

Salt tolerance of cells of halophytes is mainly achieved by four different mechanisms, e.g., (a) osmotic adjustment of the cytoplasm due to the accumulation of compatible solutes, such as betaine, proline, or sugar alcohol (Wang et al. 2004), (b) salt extrusion from the cell across the plasma membrane using ion transporters (Shi et al. 2000), (c) salt accumulation in vacuoles using tonoplast transporters (Gaxiola et al. 1999) and (d) triggering on the elevated production of antioxidative enzymes for scavenging ROS (Dasgupta et al. 2010). The exposure to NaCl imposes oxidative stress in halophytes due to changes in the osmotic and ionic environment of the cell (Hasegawa et al. 2000). It is now well accepted that ROS production is aggravated in salt stress-imposed plants and antioxidative enzymes are responsible for quenching of these ROS (Imlay 2003). There are several reports of up regulation of antioxidative enzymes and their corresponding genes in halophytes, especially mangroves under salinity (Jithesh et al. 2006a; Ben Amor et al. 2005; Cherian and Reddy 2003; Cherian et al. 1999). Increased activities of the antioxidant enzymes, e.g., superoxide dismutase and catalase were observed in *Bruguiera gymnorrhiza*, after shifting from water to high salinity (Takemura et al. 2000). Similarly, enhancement in the content of H_2O_2 as well as in the activity of APX, guaiacol peroxidase (GPX), GR and SOD was observed in *B. parviflora* after salt treatment (Parida et al. 2004). However, in *A. corniculatum*, concomitant decrease in antioxidative enzymes such as catalase, ascorbate peroxidase and guaiacol peroxidase is seen with increase in period of salt treatment (Mishra and Das 2003). In *S. maritima* significant accumulation of H_2O_2 was observed along with increment in the activity of CAT and SOD after high salt treatment (Mallik et al. 2011). Salinity-imposed increment in antioxidant enzymes (peroxidase and SOD) was observed in seven mangrove plants such as *Aegialitis rotundifolia, Heritiera fomes, X. granatum, X. mekongensis, B gymnorrhiza, E. agallocha* and *Phoenix paludosa* (Dasgupta et al. 2010, 2012). In the shoots of

Salicornia brachiata, salt treatment preferentially enhanced the activities of APX, POX, GR and SOD, whereas it induced the decrease of catalase activity. Similarly, salinity caused an increase in total glutathione content (GSH + GSSG) and a decrease in total ascorbate content. The long-term exposure of *S. brachiata* to salinity induced a 135–149 % increase in the SOD activity. Further, parameters of oxidative stress such as malondialdehyde (MDA), a product of lipid peroxidation and H_2O_2 concentrations, have shown increasing trend with increment in salinity (Parida and Jha 2010). However, enhanced activities of antioxidant enzymes such as superoxide dismutase, catalase and peroxidase were observed especially in shoots of *C. maritimum* with increase in NaCl concentration (Ben Amor et al. 2005). Further, Ru et al. (2009) have reported that the ability of *K. candel* to tolerate high salt concentration was possible due to induction of soluble sugars, proline and increase in the activities of SOD and POD.

Several salt stress-associated genes from mangroves have been evaluated for their contribution to salt tolerance indicating the tolerance of mangroves to a high-saline environment is indeed tightly linked to the regulation of gene expression. The expression of antioxidant genes such as Cu–Zn-SOD (Sod1), catalase (Cat1) and ferritin (Fer1) in response to salt, iron, hydrogen peroxide, mannitol and light stress was reported by mRNA expression analysis in *A. marina* (Jithesh et al. 2006b). In response to NaCl stress Cat1, Fer1 showed short-term induction while Sod1 transcript was found to be unaltered, thus confirming their role in oxidative stress response. Similarly, it was observed Cu/Zn-SOD transcript was induced by high salinity in young and mature leaves rather than in old leaves in *B. gymnorrhiza* (Takemura et al. 2002).

Progress in antioxidant studies of mangrove plants

Several mangrove species are used in traditional medicine and represent a great resource for unique metabolites with wide range of phytochemicals and biological activities (Bandaranayake 1998; Patra et al. 2009a, b; Patra and Thatoi 2011). They are highly resistant to salinity and tidal fluctuations and are known to be a source of several bioactive compounds and secondary metabolites such as alkaloids, phenolics, tannins, flavonoids, steroids and terpenoids with toxicological and pharmacological importance (Patra et al. 2011; Bandaranayake 2002; Patra and Thatoi 2011) (Table 2). Though several mangroves are extensively used in traditional medicine, only some of them were tested for biological activities and a very few were studied for antioxidant activity. A number of biological activities such as antibacterial, anticancer, cytotoxic, antiproliferative, insecticidal, antimalarial, antifungal, antifeedant, antidiarrheal, central nervous system depressant, antimitotic, antileukemic and antiplasmodial activities have been detected in mangrove plants (Patra et al. 2011; Ravikumar and Gnanadesigan 2011a; Banerjee et al. 2008). Since mangrove plants grow in the environmental stress conditions they are equipped with strong antioxidant activities to withstand the stress. The antioxidant properties of the mangrove plants along with their therapeutic potential as reported by various authors are summarized in Table 3.

The genus *Acanthus* belongs to the family Acanthaceae, and has four mangrove-associated species—*A. ebracteatus, A. ilicifolius, A. volubilis*, and *A. xiamenensis*. However, the antioxidant activity of only *A. ilicifolius* has been reported so far. Recently, some studies have appeared on antioxidant activity of the ethanol extracts of leaf (Li et al. 2009; Thirunavukkarasu et al. 2011a) and roots (Thirunavukkarasu et al. 2011b) of *A. ilicifolius* in in vitro conditions which showed that the plant possesses strong antiradical properties against the harmful free radicals. Similarly, the antioxidant activity of the methanol extract of flowers has been reported (Firdaus et al. 2013) and that of the leaf and roots extracts has been reported (Banerjee et al. 2008). The in vivo antioxidant potential of the methanol extracts of *A. ilicifolius* has also been reported by Asha et al. (2012) which was found to be beneficial in ameliorating the oxidative stress in brain of rats that may be attributed to its higher flavonoids and phenolic contents.

Few workers have reported the antioxidant property of the mangrove plant *Aegiceras corniculatum*. The *n*-hexane, ethyl acetate and methanol extracts of stem of *A. corniculatum* exhibited pronounced scavenging action against various radicals ($O_2^{\cdot-}$, OH·, LOO·), chelate metal ions, inhibit the lipid peroxidation, diminish the respiratory burst in cells and also exert a protective effect against oxidative damage by ·CCl3 in rat liver and by OH· in mouse paw. The phenolic constituents from *A. corniculatum* mainly comprising of flavonoids (kaempferol), flavonol (quercetin and isorhamnetin), triterpenes having oleanane and β-amyrin skeleton (aegicerin, aegiceradienol and genin-A), phenolic acids (gallic acid and syringic acid) and stilbene (resveratrol) have been attributed for their antioxidant potentials (Roome et al. 2008). Similarly, the aqueous methanol extracts of stem bark, leaves and roots of *A. corniculatum* also showed remarkable high-phenolic content (GAE > 25 mg/g), strong reducing ability (ascorbic acid equivalent, AAE > 3.5 mg/g) and antiradical activity (IC_{50} < 2.9 mg/ml) (Banerjee et al. 2008). Studies conducted by Agoramoorthy et al. (2008) reported that methanol extracts of *A. corniculatum* can be a vital source of antioxidant phytochemicals. A bioactive compound rapanone isolated from the extracts of *A. corniculatum* exhibits mild antioxidant activity (Ospina et al. 2001).

Table 2 Major antioxidant compounds isolated from some mangrove plants

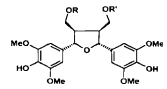
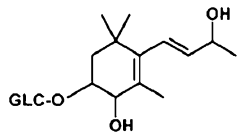
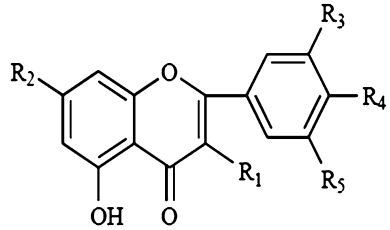
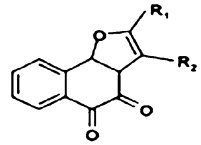
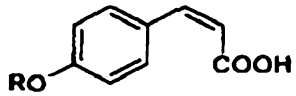
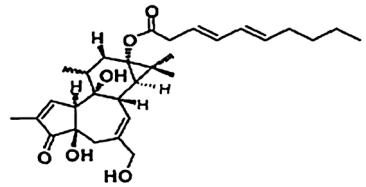
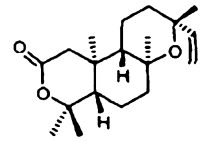
Mangrove plant	Plant part	Name of the compound	Chemical structure	References
Acanthus ilicifolius, Avicennia marina	Leaf, twigs	Dihydroxymethyl-bis (3,%dimethoxy-4-hydroxyphenyl) tetrahydrofuran-9 (of 9′)-O-fl-glucopyranoside (flavonoids)		Singh et al. (2009), Sun et al. (2009)
Acanthus ebracteatus	Whole plant	Sesquiterpenoid plucheoside B (terpenoids)		Kanchanapoom et al. (2001)
Avicennia marina	Whole plant	4′,5,7-trihydroxyflavone (flavonoids)		Prabhu and Guruvayoorappan (2012)
Avicennia marina	Stem, whole plant	Phytoalexins		Bandaranayake (2002), Khafagi et al. (2003)
Calophyllum inophyllum, Thespesia populnea	Bark	Glycosidic coumarin derivatives		Datta et al. (1973), Bandaranayake (2002)
Excoecaria agallocha	Twigs and bark	12-Deoxyphorbol-13(3E,5E)decadienoate		Erickson et al. (1995), Liebezeit and Rau (2006)
Excoecaria agallocha	Leaf	Agallochin E		Anjaneyulu and Rao (2000), Jun et al. (2008), Zhu et al. (2009), Bandaranayake (2002)

Table 2 continued

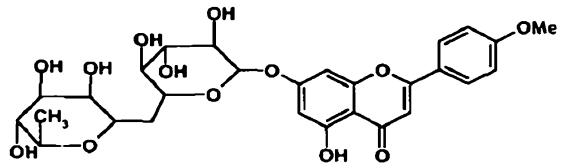
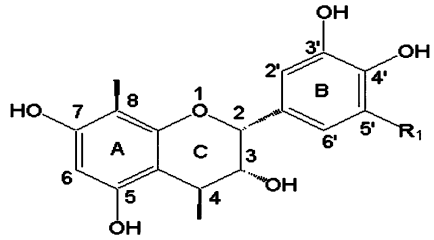
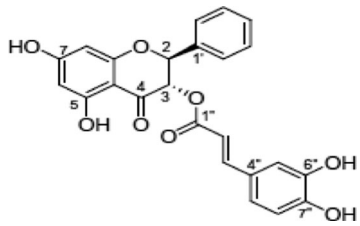
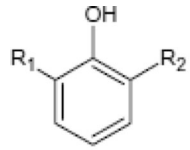
Mangrove plant	Plant part	Name of the compound	Chemical structure	References
Excoecaria agallocha	Stem and twigs	Acacetin 7-O-a-L-rhamnopyranosyl-(l'' → 6'')-O-fl-glucopyranoside (flavonoids)		Li et al. (2010)
Kandelia candel, Rhizophora mangle	Leaf	Epigallocatechin (tannin)		Zhang et al. (2010)
Laguncularia racemosa	Twig and barks	Dihydroflavone (phenolics)		Shi et al. (2010)
Rhizophora apiculata	Pyroligneous acid	Syringol	 R1, R2 = OCH_3	Loo et al. (2008)

Table 3 Antioxidant properties of some selected mangrove plants

Plant species	Regional name	Plant parts	Therapeutic uses	References
Acanthus ilicifolius L.	Harakancha (Oriya)	Leaf, stem, root, flower	Leaves, barks and total plants are used as blood purifier, diuretic and aphrodisiac; it is applied for curing diabetes, leprosy, paralysis, skin disease, snake bite, hepatitis, stomach pain, rheumatism, asthma, etc.	Banerjee et al. (2008), Li et al. (2009), Thirunavukkarasu et al. (2011a, b); Firdaus et al. (2013), Asha et al. (2012)
Aegiceras corniculatum L.) Blanco	Kharsi (Oriya, Bengali), Halsi (Hindi), Narikandam (Tamil), Dudumara (Telugu)	Leaf, stem/ bark, root	Leaves are used for curing boil, earache, small pox; seeds and barks are used for curing asthma, diabetes, rheumatism, etc.	Banerjee et al. (2008), Roome et al. (2008), Agoramoorthy et al. (2008), Ospina et al. (2001)
Avicennia alba Bl.	Kala bani (Oriya)	Leaf, stem/ bark, root	Leaves and barks are used in antifertility treatment, skin diseases, ulcers, etc.; it is also used as contraceptive	Banerjee et al. (2008)
A. marina (Forsk.) Vierh.	Bani (O)	Leaf, stem/ bark, root	Leaves are used as an astringent and for curing ulcers, small pox, etc.	Thirunavukkarasu et al. (2011a, b), Vadlapudi and Naidu (2009), Shanmugapriya et al. (2012), Beula et al. (2012)
A. officinalis L.	Dhala bani (O)	Leaf, stem/ bark, root	Seed, root, barks are used for curing boils, small pox, leprosy, relieving ulcers; it is also used as diuretic and aphrodisiac	Thirunavukkarasu et al. (2011a, b), Vadlapudi and Naidu (2009), Ravindran et al. (2012), Shanmugapriya et al. (2012), Beula et al. (2012)
Bruguiera gymnorrhiza (L.) Lamk.	Bandari (Oriya), Kekra (Oriya), Kankra (Bengali)	Leaf, stem/ bark, root	Bark is used as astringent and also for curing malaria; fruit are also used as astringent; treatment of eye disease and as fish poison etc.	Banerjee et al. (2008), Haq et al. (2011)
Bruguiera cylindrica (L.) Bl.	Kakandan (Hindi), Vurada (Telugu)	Leaf, stem/ bark	Leaves are used as cure for hepatitis; it is a good source of tannin	Agoramoorthy et al. (2008), Krishnamoorthy et al. (2011)
Bruguiera parviflora (Roxb.)	Smallflower Bruguiera	Edible pods	Bark is used in constipation; it is also a good antitumor agent	Bunyapraphatsara et al. (2003)
Ceriops decandra (Griff.) Ding	Ghrani (Oriya)	Leaf, stem/ bark, root edible pods	Root and bark are used for curing hepatitis, hemorrhage and malaria; fruit paste are used against ulcers	Banerjee et al. (2008), Krishnamoorthy et al. (2011), Bunyapraphatsara et al. (2003)
Ceriops tagal (Perr.) Robins.	Goran (Hindi), Gari Goran (Oriya) Mat Goran (Bengali)	Edible pods	Leaves are used as purgative and to stop hemorrhages; it is also used for curing leprosy; shoot is used as decoction for treatment of malaria	Bunyapraphatsara et al. (2003)
Excoecaria agallocha L.	Guan (Oriya), Genwa (Bengali), Kampetti (Tamil), Thilla (Telugu)	Leaf, stem/ bark	Leaves are used for curing epilepsy, ulcers, etc.; roots are used for curing hand and feet swelling, leprosy, toothache, conjunctivitis, dermatitis, etc.; it is also used as uterotonic, purgative, fish poison; milky latex is used against paralysis	Patra et al. (2009a), Konishi et al. (1998), Konishi et al. (2000), Masuda et al. (1999), Subhan et al. (2008), Ravindran et al. (2012), Arumugam et al. (2012)
Heritiera fomes Buch.-Ham.	Sundari (Oriya, Bengali)	Stem and leaf	Bark is used for healing wound and cuts; seeds are eaten as source of nutrients	Wangensteen et al. (2009)
Kandelia candel (L.) Druce	Sindukua (Oriya), Goria (Bengali), Thuvarkandu (Tamil), Kandigala (Telugu)	Hypocotyl, Leaf	Bark mixed with dry ginger in water is used for curing diabetes	Wei et al. (2011), Zhang et al. (2010), Ravindran et al. (2012)
Lumnitzera racemosa Willd.	Tunda (Oriya), Kripa (Bengali), Kandivi (Telugu)	Leaf	Stem is used for curing itches and herpes, asthma, diabetes, snake bite, etc.; it is also used as an antifertility agent	Bunyapraphatsara et al. (2003), Ravikumar and Gnanadesigan (2011a)

Table 3 continued

Plant species	Regional name	Plant parts	Therapeutic uses	References
Laguncularia racemosa (L) Gaertn. f.	–	Twig, bark	A bark infusion is historically used as an astringent and tonic, and as a folk remedy for dysentery, aphthae, fever and scurvy	Shi et al. (2010)
Pandanus odoratissimus		Leaf, stem/ bark	Possess strong antioxidant properties	Jun et al. (2008)
Rhizophora apiculata Bl.	Rai (Oriya)	Leaf, stem/ bark, roots	Leaves are used for curing diarrhea, skin diseases; bark is used for treatment of nausea, hepatitis, vomiting, typhoid; it is also used as antiseptic, insecticide, etc.	Agoramoorthy et al. (2008), Dong et al. (2007), Beula et al. (2012), Asha et al. (2012)
Rhizophora mangle	Rai (Oriya)	Leaf, Stem/ bark	Possess strong antioxidant properties	Zhang et al. (2010)
Rhizophora mucronata Lamk.	Rai (Oriya)	Leaf, stem/ bark, root	Bark is used for curing diabetes, hemorrhage, hepatitis, ulcer, dysentery, etc.; the bark is powerful astringent	Banerjee et al. (2008), Agoramoorthy et al. (2008), Bunyapraphatsara et al. (2003), Beula et al. (2012), Ravindran et al. (2012)
Rhizophora stylosa	Samudra Rai (Oriya)	Leaf, stem/ bark	The bark is used for dye making and folk medicine. The extracts possess antifungal, antibacterial, antiulcer and antioxidant properties	Takara et al. (2008), Dong et al. (2007)
Sesuvium portulacastrum L.	Goda bani (Oriya)	Leaf, stem, root	Young plants are edible after boiling to remove excess salt from body	Banerjee et al. (2008)
Sonneratia alba J. Smith	Padda Kalinga, Pedata (Marathi)	Calyx, bark	Leaves and bark is used for curing hemorrhages, piles, Skin disorders, etc.	Bunyapraphatsara et al. (2003), Milon (2012)
Sonneratia apetala Buch.-Ham.	Keruan (Oriya)	Leaf, stem/ bark, root, seeds	Fruits are edible as source of natural antioxidant; Leaves and roots are used in the treatment of stomach pain, rheumatism, etc.	Banerjee et al. (2008), Vadlapudi and Naidu (2009), Hossain et al. (2013)
Sonneratia caseolaris (L.) Engler	Archa (Bengali), Ora (Bengali), Orcha (English)	Calyx	Leaf decoction is used against diarrhea; it is used as skin protection	Bunyapraphatsara et al. (2003)
Suaeda maritima Dumort	Giria saga (Oriya)	Leaf, stem, root	Whole plant is used for curing hepatitis	Patra et al. (2011), Banerjee et al. (2008), Thirunavukkarasu et al. (2011a, b), Ravikumar et al. (2011)
Terminalia catappa	Katha badam (Oriya)	Leaf, stem	Possesses remarkably potent antioxidant activity	Masuda et al. (1999)
Xylocarpus rumphii	–	Calyx	Strong antioxidant potential	Bunyapraphatsara et al. (2003)
Xylocarpus granatum Koenig	Pussur (H), Susumara (O), Dhundul (B)	Leaf, stem	Bark is used for treatment of dysentery, diarrhea, febrifuge, malaria, cholera, insect bite, swelling of breast, etc.; it is also used as an astringent	Vadlapudi and Naidu (2009)

There are three species of genus *Avicennia* (family Avicenniaceae) viz. *A. marina, A. alba* and *A. officinalis,* all of which are tree species. A few studies have been reported on the antioxidant potential of leaf extracts of these plant species. Thirunavukkarasu et al. (2011b) have reported the highly effective antioxidant potential of ethanol and aqueous extracts of leaf of *A. officinalis* using various in vitro assay systems such as DPPH, superoxide, and hydroxyl radical scavenging activities and total phenolic activity as well as inhibition of protein oxidation and reducing power. Study on antioxidant properties of four mangrove plants, e.g., *A. marina, A. officinalis, Rhizophora mucronata* and *R. apiculata* has been conducted, in which the leaf extract of *A. marina* has shown highest antioxidant activity (Beula et al. 2012). The antioxidant IC_{50} values of *A. marina* were identified as 12.80 ± 0.93, 640.06 ± 34.93, 19.91 ± 3.93 and 142.06 ± 17.93 μg/mL concentrations for SOD, LPO, NO and DPPH assays,

respectively. Evaluation of antioxidant potential for superoxide scavenging, DPPH free radical scavenging, catalase, ascorbic acid content of methanol leaf extracts of all the three species of *Avicennia* plant have been reported to possess promising antioxidant properties (Vadlapudi and Naidu 2009). The comparative evaluation of the antioxidant potential between *A. marina* and A. *officinalis* showed that the leaf extracts of *A. marina* have more effective antioxidant activity than that of the leaf extracts of *A. officinalis* (Shanmugapriya et al. 2012). The antioxidant potential of the aqueous methanol extracts of stem bark, leaves and roots of *A. alba* was studied using 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical scavenging assay and reported moderate antioxidant potential of the extracts (Banerjee et al. 2008). The antioxidant potential of *A. officinalis* and their respective endophytic fungi was also studied, which adds our understanding in the mutualistic associations of plant and endophyte against various biotic and abiotic stresses (Ravindran et al. 2012).

Genus *Bruguiera* comprises three species viz. *Bruguiera cylindrical*, *B. gymnorrhiza* and *B. parviflora*. Studies on antioxidant potential of edible pods of *B. parviflora* by Bunyapraphatsara et al. (2003) have reported possession of strong antioxidant activity of the plant. A few recent studies have reported the antioxidant potential of this plant species in. In vitro antioxidant assays such as DPPH, ABTS, OH· scavenging assay and reducing capacity of methanol extracts of leaf of *B. cylindrica* have shown its potential free radicals scavenging activity (Agoramoorthy et al. 2008). The antiradical activity of aqueous and methanol extracts of stem bark, leaves and roots of *B. gymnorrhiza* was also reported by Banerjee et al. (2008). The antioxidant activity of the crude methanolic, ethanolic and chloroform extracts of leaves and barks of *B. gymnorrhiza* was evaluated using the enzymatic and non-enzymatic methods namely SOD determination, reducing power assay and DPPH assay (Haq et al. 2011). It was observed that the ethanol extract of the barks of this plant possesses strong antioxidant potential which was positively co-related with the total phenolic contents. The methanol extract of stem bark of *B. cylindrica* exhibiting high-antiradical activity against DPPH, ABTS and OH· radicals with good dose-dependent reductive capacity has been reported by Krishnamoorthy et al. (2011).

The antioxidant potential of extracts of two species of genus *Ceriops*, *Ceriops decandra* and *C. tagal* has been reported by a few workers so far. The edible pods of *C. decandra* and *C. tagal* showed strong antioxidant activity (Bunyapraphatsara et al. 2003). In a study conducted by Banerjee et al. (2008), the methanol extracts of bark of *C. decandra* where the total phenolics calculated as gallic acid equivalent (GAE) and antiradical activity estimated as IC_{50} values using DPPH have shown strong antioxidant activities. Studies have shown that *C. decandra* have the potential in scavenging free radicals and can be a vital source of antioxidant phytochemicals. The DPPH radical scavenging activity of *C. decandra* was also found to be 51.9 μg/mL as studied by Agoramoorthy et al. (2008). The methanol stem bark extract of *C. decandra* also showed good dose-dependent reductive capacity (Krishnamoorthy et al. 2011).

The genus *Excoecaria* belonging to the family Euphorbiaceae have two species, *Excoecaria indica* and *E. agallocha*. Reports on antioxidant properties of *E. indica* are not available so far. A number of antioxidant studies have been reported in *E. agallocha* so far. Studies on aqueous extract of *E. agallocha* collected from the mangrove forests of Bhitarkanika (India) revealed promising antioxidant properties for various antioxidant assays such as DPPH radical scavenging, reducing power, H_2O_2 scavenging assay, etc. (Patra et al. 2009a). The infusion of leaves of *E. agallocha* was reported to possess strong antioxidant properties (Konishi et al. 1998, 2000). As evident from three kinds of assays such as DPPH radical scavenging assay, linoleic acid oxidation assay and oxidative cell death assay the methanolic extracts of the leaves of *E. agallocha* were reported to possess remarkably potent antioxidant activity (Masuda et al. 1999). The HPLC analysis of the methanolic extracts of *E. agallocha* indicated the presence of ellagic acid as the potent antioxidant agent. The hydro-alcohol extract of the dried and ground bark of *E. agallocha* has been assessed for antioxidant activity using a series of well-established assays including the DPPH, the lipid peroxidation by thiobarbituric acid (TBA), the reducing power, the nitric oxide (NO·) and the hydrogen peroxide (H_2O_2) scavenging assays (Subhan et al. 2008). The results showed that in the DPPH, the NO and the H_2O_2 scavenging assays, the extract of *E. agallocha* displayed significant antioxidant activities with the IC_{50} values of 179.16, 120.24 and 134.29 μg/ml, respectively. The reducing power of the extract increased dose-dependently and the extract reduced the most Fe^{3+} ions to the extent less than butylated hydroxy toluene (BHT). In the lipid peroxidation assay, the extract showed significant inhibition of peroxidation effect at all concentrations, with an IC_{50} value of 189.27 μg/ml. Leaf and root extracts of *E. agallocha* had lower EC_{50} values and higher or equivalent percentage inhibition in comparison with the BHT standard. Similarly, studies have shown that the leaf extract of *E. agallocha* had maximum metal-chelating activity in comparison to *A. officinalis, K. candel* and *R. mucronata* (Ravindran et al. 2012). The antioxidant activity of the field and micropropagated plant leaves of *E. agallocha* was also reported using various in vitro assay methods (DPPH, total phenols, ascorbic acid content). The findings had shown remarkable DPPH scavenging activity (IC_{50} of

10.2 μg/ml), total phenolic content (205 mg/GAE/g) and ascorbic acid contents (18 mg l^{-1} $plant^{-1}$) (Arumugam et al. 2012).

The genus *Heritiera* (family Sterculiaceae) have three species, viz. *Heritiera littoralis, H. fomes*, and *H. globosa*. The antioxidant properties of *H. littoralis* and *H. globosa* are not reported so far. The antioxidant potential of ethanol extracts of stem bark of *H. fomes* was evaluated in terms of DPPH radical scavenging assay and 15-lipoxygenase inhibiting activities reported to have remarkably high-antioxidant activity (Wangensteen et al. 2009). It was found that the extracts were rich in procyanidins as the antioxidant agent.

The *Kandelia candel* belongs to the genus *Kandelia* (family Rhizophoraceae) and has been studied by different workers for its antioxidant properties. The antioxidant potential of 70 % acetone extract from the hypocotyls of *K. candel* and its different fractions (petroleum ether, ethyl acetate, water and the water fraction further purified through a Sephadex LH-20 column) were investigated by the DPPH free radical scavenging and FRAP assays reported to possess potent antioxidant activity (Wei et al. 2011). Similar studies with aqueous extract of leaves of *K. candel* also revealed that the condensed tannin oligomers are responsible for its strong antioxidant activity (Zhang et al. 2010). The antioxidant potential of methanol extracts of leaves and root samples of *K. candel* seedling studied using various in vitro assay techniques such as iron chelating capacity, reducing power, and hydroxyl radicals/hydrogen peroxide/DPPH radical scavenging and inhibition of lipid peroxidation using the β-carotene-linoleate model system showed strong antioxidant property of the plant extract (Ravindran et al. 2012).

The antioxidant property of ethanol extracts of leaf of *Lumnitzera racemosa* was reported using various in vitro assays such as DPPH, HRSA, NO, FRAP, LPO and SOD (Ravikumar and Gnanadesigan 2011a). Ravikumar and Gnanadesigan (2011a) have reported that the ethanolic extract of *L. racemosa* possesses significant hepatoprotective effect in CCl_4 intoxicated Wistar albino rats as it has significantly reduced all elevated biochemical parameters such as SGPT, SGOT, ALP, LDH and bilirubin levels. The methanol extracts of leaves and fruits of *L. racemosa* have shown strong antioxidant activity (Bunyapraphatsara et al. 2003). The antioxidant potential of the phenolic compounds isolated from the ethanol extract of bark and twigs of Chinese mangrove plant *Laguncularia racemosa* (L) Gaertn.f. (Combretaceae) has been evaluated and the result has shown significant antioxidative activity in various in vitro assay methods viz. in the DPPH and TEAC free radical scavenging assays (Shi et al. 2010).

All the four species of genus *Rhizophora*, *R. apiculata, R. mangle, R. mucronata, R. stylosa,* have been reported to exhibit antioxidant properties. The 70 % aqueous acetone extract of bark and the dichloromethane extract of the pyroligneous acid of *R. apiculata* have shown strong antioxidant property as evaluated by various in vitro assay methods viz. DPPH assay, ABTS assay, phosphomolybdenum and FRAP assay (Rahim et al. 2008; Loo et al. 2008). In vivo study of ethanol extracts of root of *R. apiculata* on rats has shown that they have better antioxidant activity than *A. ilicifolius* and had protective effect on sodium nitrite-induced oxidative stress in brain of rats (Asha et al. 2012). The aqueous extract of leaves of *R. mangle* was found to be rich in antioxidant properties as revealed by various in vitro antioxidant assays such as Folin–Ciocalteu, DPPH, and ORAC assay. The aqueous extracts of bark of *R. mangle*, the red mangrove, was studied for its gastro-protective effect. The results showed that the highest dose of the extract provoked a marked increase in glutathione peroxidase and superoxide dismutase activity, which was comparable to omeprazole (Berenguer et al. 2006). In another study, Zhang et al. (2010) have reported that the aqueous extracts of leaves of *R. mangle* possess strong antioxidant activity and the presence of condensed tannin monomers such as (epi) catechin and catechin (epi) heteroside was responsible for its potent antioxidant activity. The methanolic leaf extract of *R. mucronata* have shown promising antioxidant potential as revealed by various in vitro antioxidant assays, including DPPH, nitric oxide, hydrogen peroxide, hydroxyl radical scavenging assay, reducing power, ferrous ion chelating and lipid peroxidation inhibition assay (Ravindran et al. 2012; Suganthy et al. 2009). As evident by various in vitro antioxidant assay methods, the antioxidant activity of *R. mucronata* was also seen in the aqueous methanol extracts of stem bark, leaves and roots (Banerjee et al. 2008), methanol extracts of edible pods (Bunyapraphatsara et al. 2003) and the ethanol extracts of different parts (bark, collar, hypocotyls and stilt roots) (Ravikumar and Gnanadesigan 2011b). The flavonol derivatives such as flavan-3-ol glycosides along with flavan-3-ol found in the ethanol extracts of stem of *R. stylosa* have exhibited strong antioxidant activity (Takara et al. 2008; Dong et al. 2007) in terms of DPPH assay.

Out of the two species of *Suaeda* (family Chenopodiaceae), *Suaeda maritima* and *S. monoica,* the antioxidant property of *S. Maritima* has been reported so far. The methanol extracts of aerial part (Banerjee et al. 2008) and the different solvent extracts (acetone, ethanol, methanol and aqueous) of leaves and stems (Patra et al. 2011) have shown strong antioxidant activity as revealed by various antioxidant activities viz. DPPH assay, NO scavenging assay, ferrous ion chelating assay, metal ion chelating assay, TAC assay, total phenol content, reducing activity. In another study, the hepatoprotective and antioxidant properties of ethanolic extract of leaves of *S. maritima*

were observed in concanavalin-A-induced rats. The results of the study showed very promising hydroxyl and nitric oxide radicals scavenging activity of the extract of *S. maritima* comparable with vitamin C (Ravikumar et al. 2011).

All the three species of genus *Sonneratia* (family Sonneratiaceae), *S. apetala, S. alba* and *S. caseolaris,* have been reported to exhibit antioxidant properties. As studied under various enzymatic and non-enzymatic in vitro assay methods, the aqueous and methanol extracts of stem bark, leaves and roots (Banerjee et al. 2008), methanol extracts of leaves, stem bark and flowers (Vadlapudi and Naidu 2009) and the methanol extracts of pericarp and seed of the fruit (Hossain et al. 2013) of *S. apetala* have shown strong antioxidant activities. Similarly, studies on methanol extracts of calyces (Bunyapraphatsara et al. 2003) and the carbon tetrachloride, chloroform soluble partitionate of methanolic extract and crude methanolic extract of bark (Milon 2012) of *S. alba* have shown strong antioxidant activity as well as strong anti-lipid peroxidation activity. The antioxidant potential of methanol extracts of calyces of *S. caseolaris* was also reported by Bunyapraphatsara et al. (2003).

Antioxidant potential of aqueous extract of leaves of *Terminalia catappa,* a mangrove associate, was studied on bleomycin-induced Chinese hamster ovary cells and reported that a major tannin known as punicalagin is responsible for its antioxidative properties (Chen et al. 2000). The methanol extracts of the leaves of *T. catappa* have also shown antioxidant activity under in vitro conditions in three kinds of assay methods such as the DPPH radical scavenging assay, linoleic acid oxidation assay, and oxidative cell death assay (Masuda et al. 1999). The HPLC analysis of the methanol extracts indicated the presence ellagic acid is responsible for its strong antioxidant activity in the leaves of *T. catappa* (Masuda et al. 1999). The genus *Xylocarpus* belongs to the family Meliaceae and has four mangrove species—*X. granatum, X. rumphii, X. mekongensis* and *X. moluccensis.* The antioxidant potential of methanol extracts of fruit peel and branches of *X. rumphii* has been reported by Bunyapraphatsara et al. (2003). Antioxidant activity of methanol leaf extract of yet another species *X. granatum* has also shown to possesses strong antioxidant activity as evident by various antioxidant assays such as DPPH, FRAP, SOD, catalase assay, etc. (Vadlapudi and Naidu 2009).

Studies undertaken so far establish the potential of mangrove plants for their antioxidants bioactive substances. Mangroves comprise a limited number of plant species; however, few plants have been screened for their antioxidant potential. These studies, however, are preliminary in nature and not all the plants have been screened so far. Not much progress has been made in characterization and identification of bioactive compounds from mangrove species so that it could exploit for pharmaceutically important drug development. It is now important to undertake studies in detail in this direction for potentially antioxidant plants from mangrove species which has proved for their very efficient antioxidant capacity.

Conclusion

Oxidative stress is a condition in which ROS or free radicals are generated extra- or intracellularly, which can exert their toxic effects to the cells. An increase in the antioxidant reserves of the organism can reduce oxidative stress and some of the plant-derived agents may help to reduce it. Currently, there has been an increased interest globally to identify antioxidant compounds from plant sources which are pharmacologically potent and have low or no side effects for use in protective medicine. Mangrove plants inhabiting a very hostile environment conditions are exposed to enhance ROS production, and consequently, the concentration and activity of the antioxidative enzymes are high in these species to neutralize the ROS. Research findings revealed that almost all mangrove plants are endowed with rich source of antioxidant compounds which can be categorized into different types such as enzymatic, non-enzymatic, nutritional, phytoconstituents and phytonutrients. Consolidated research with advanced molecular, pharmaceutical linkage is required to investigate the mechanism of antioxidant activity of these stress tolerant plants for their potential applications in therapeutics.

Author contribution Dr. H. N. Thatoi and Dr. J. K. Patra have conceptualized and designed the idea. They have searched the literature and have contributed immensely in preparation of the article. S. K. Das has searched the literature, and contributed in tabulation of information and preparation of the article particularly in progress of antioxidant study in mangroves portion of the review article. All the authors have contributed in compilation of the information. Dr. Thatoi has edited the whole manuscript.

References

Agoramoorthy G, Chen F, Venkatesalu V, Kuo D, Shea P (2008) Evaluation of antioxidant polyphenols from selected mangrove plants of India. Asian J Chem 20:1311–1322

Ali SS, Kasoju N, Luthra A, Singh A, Sharanabasava H, Sahu A, Bora U (2008) Indian medicinal herbs as sources of antioxidants. Food Res Int 41:1–15

Alia PSP, Pardhasaradhi P, Mohanty P (1991) Proline enhances primary photochemical activities in isolated thylakoid

membranes of *Brassica juncea* by arresting photoinhibitory damage. Biochem Biophys Res Commun 181:1238–1244

Amado LL, Jaramillo MD, Rocha AM, Ferreira JLR, Garcia LM, Ramos PB (2007) A new method to evaluate total antioxidant capacity against reactive oxygen and nitrogen species (RONS) in aquatic organisms. Comp Biochem Physiol Part A Mol Integr Physiol 148:S75–S76

Anjaneyulu ASR, Rao VL (2000) Five diterpenoids (agallochins A–E) from the mangrove plant *Excoecaria agallocha* Linn. Phytochemistry 55:891–901

Apak R, Guculu KG, Ozyurek M, Karademir SE (2004) Novel total antioxidant capacity index for dietary polyphenols and vitamins C and E, using their cupric iron reducing capability in the presence of neocuproine: CUPRAC method. J Agric Food Chem 52:7970–7981

Arora A, Sairam RK, Srivastava GC (2002) Oxidative stress and antioxidant system in plants. Cur Sci 82:1227–1238

Arumugam M, Pawar UR, Gomathinayagam M, Lakshmanan GMA, Panneerselvam R (2012) Antibacterial and antioxidant activity between micropropagated and field grown plants of *Excoecaria agallocha* L. Int Res J Pharm 3:235–240

Asada K (2006) Production and scavenging of reactive oxygen species in chloroplasts and their functions. Plant Physiol 141:391–396

Asada K, Kiso K, Yoshikawa K (1974) Univalent reduction of molecular oxygen by spinach chloroplasts on illumination. J Biol Chem 249:2175–2181

Asha KK, Mathew S, Lakshmanan PT (2012) Flavonoids and phenolic compounds in two mangrove species and their antioxidant property. Int J Geo-Mar Sci 41:259–264

Athukorala Y, Kim KN, Jeon YJ (2006) Antiproliferative and antioxidant properties of an enzymatic hydrolysate from brown alga, *Ecklonia cava*. Food Chem Toxicol 44:1065–1074

Bandaranayake WM (1998) Traditional and medicinal uses of mangroves. Mangroves Salt Marshes 2:133–148

Bandaranayake WM (2002) Bioactivities, bioactive compounds and chemical constituents of mangrove plants. Wetl Ecol Manag 10:421–452

Banerjee D, Chakrabarti S, Hazra AK, Banerjee S, Ray J, Mukerjee B (2008) Antioxidant activity and total phenolics of some mangroves in Sundarbans. Afr J Biotechnol 7:805–810

Ben Amor N, Ben Hamed K, Debez A, Grignon C, Abdelly C (2005) Physiological and antioxidant responses of the perennial halophyte *Crithmum maritimum* to salinity. Plant Sci 68:889–899

Berenguer B, Sánchez LM, Quílez A, López-Barreiro M, De Haro O, Gálvez J, Martín MJ (2006) Protective and antioxidant effects of *Rhizofora mangla* L against NSAID-induced gastric ulcers. J Ethnopharmacol 103:194–200

Beula JM, Gnanadesigan Rajkumar MPB, Ravikumar S, Anand M (2012) Antiviral, antioxidant and toxicological evaluation of mangrove plant from South East coast of India. Asian Pac J Trop Biomed 2:S352–S357

Bhattacharjee S (2005) Reactive oxygen species and oxidative burst: roles in stress, senescence and signal transduction in plant. Cur Sci 89:1113–1121

Bunyapraphatsara N, Jutiviboonsuk A, Sornlek P, Therathanathorn W, Aksornkaew S, Fong HHS, Pezzuto JM, Kosmeder J (2003) Pharmacological studies of plants in the mangrove forest. J Phytopharm 10:1–12

Chanda S, Dave R (2009) In vitro models for antioxidant activity evaluation and some medicinal plants possessing antioxidant properties: an overview. Afr J Microbiol Res 3:981–996

Cheeseman JM, Herendeen LB, Cheeseman AT, Clough BF (1997) Photosynthesis and photoprotection in mangroves under field conditions. Plant Cell Environ 20:579–588

Chen PS, Li JH, Liu TY, Lin TC (2000) Folk medicine *Terminalia catappa* and its major *Terminalia catappa* and its major tannin component Punicalagin are effective against bleomycin-induced genotoxicity in Chinese hamster ovary cells. Can Lett (Ireland) 152:371–376

Cherian S, Reddy MP (2003) Evaluation of NaCl tolerance in the callus cultures of *Suaeda nudiflora* Moq. Biol Plant 46:193–198

Cherian S, Reddy MP, Pandya JB (1999) Studies on salt tolerance in *Avicennia marina* (Forstk.) Vierh.: effect of NaCl salinity on growth, ion accumulation and enzyme activity. Indian J Plant Physiol 4:266–270

Chong PL, Olsher M (2007) Fluorometric assay for detection of sterol oxidation in liposomal membranes. Methods Mol Biol 400:145–158

Cízová H, Lojek A, Kubala L, Cíz M (2004) The effect of intestinal ischemia duration on changes in plasma antioxidant defense status in rats. Physiol Res 53:523–531

Cuendet M, Hostettmann K, Potterat O (1997) Iridoid glucosides with free radical scavenging properties from *Fagraea blumei*. Helv Chim Acta 80:1144–1151

Das M, Mukherjee SB, Shaha C (2001) Hydrogen peroxide induces apoptosis like death in *Leishmania donovani* promastigotes. J Cell Sci 114:2461–2469

Dasgupta N, Nandy P, Tiwari C, Das S (2010) Salinity-imposed changes of some isozymes and total leaf protein expression in five mangroves from two different habitats. J Plant Inter 3:211–221

Dasgupta N, Nandy P, Sengupta C, Das S (2012) Protein and enzymes regulations towards salt tolerance of some Indian mangroves in relation to adaptation. Trees 26:377–391

Datta SC, Murti VVS, Sharma NN, Seshadri TR (1973) Glycosidic components of *Thespesia populnea* flowers. Indian J Chem 11:506–507

Denev P, Ciz M, Ambrozova G, Lojek A, Yanakieva I (2010) Solidphase extraction of berries' anthocyanins and evaluation of their antioxidative properties. Food Chem 123:1055–1061

Dong LL, Xiao-Ming L, Ze-Yu P, Bin-Gui W (2007) Flavanol derivatives from *Rhizophora stylosa* and their DPPH radical scavenging activity. Molecules 12:1163–1169

Erickson KL, Beutler JA, Cardellina JH, McMohan JB, Newman DJ, Boyd MR (1995) A novel phorbol ester from *Excoecaria agallocha*. J Nat Prod 58:769–772

Fang ZQ, Yuan LY, Hong PC, Ming LC, Shan WB (2005) NaCl enhances thylakoid-bound SOD activity in the leaves of C3 halophyte *Suaeda salsa* L. Plant Sci 168:423–430

Firdaus M, Prihanto AA, Nurdiani R (2013) Antioxidant and cytotoxic activity of *Acanthus ilicifolius* flower. Asian Pac J Trop Biomed 3(1):17–21

Gaxiola RA, Rao R, Sherman A, Grisafi P, Alper SL, Fink GR (1999) The *Arabidopsis thaliana* proton transporters, AtNhx1 and Avp1, can function in cation detoxification in yeast. Proc Nat Acad Sci 96:1480–1485

Genard H, Le Saos J, Hillard J, Tremolieres A, Boucaud J (1991) Effect of salinity on lipid composition, glycine betaine content and photosynthetic activity in chloroplasts of *Suaeda maritime*. Plant Physiol Biochem 29:421–427

Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem 48:909–930

Gill SS, Khan NA, Anjum NA, Tuteja N (2011) Amelioration of cadmium stress in crop plants by nutrients management: morphological, physiological and biochemical aspects. Plant Stress 5:1–23

Halliwell B (2006) Reactive species and antioxidants. Redox biology is a fundamental theme of aerobic life. Plant Physiol 141:312–322

Haq M, Sani W, Hossain ABMS, Taha RM, Monneruzzaman KM (2011) Total phenolic contents, antioxidant and antimicrobial activities of *Bruguiera gymnorrhiza*. J Med Plants Res 17:4112–4118

Harrison PD, Arosio P (1996) Ferritins: molecular properties, iron storage function and cellular regulation. Biochem Biophys Acta 1275:161–203

Hasegawa PM, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. Annu Rev Plant Physiol Plant Mol Biol 51:463–499

Hollander-Czytko H, Grabowski J, Sandorf I, Weckermann K, Weiler EW (2005) Tocopherol content and activities of tyrosine aminotransferase and cystine lyase in *Arabidopsis* under stress conditions. J Plant Physiol 162:767–770

Hossain SJ, Basar MH, Rokeya B, Arif KMT, Sultana MS, Rahman MH (2013) Evaluation of antioxidant, antidiabetic and antibacterial activities of the fruit of *Sonneratia apetala* (Buch.-Ham.). Orient Pharm Exp Med 13:95–102

Huang GY, Wang YS, Sun CC, Dong JD, Sun ZX (2010) The effect of multiple heavy metals on ascorbate, glutathione and related enzymes in two mangrove plant seedlings (*Kandelia candel* and *Bruguiera gymnorrhiza*). Oceanol Hydrobiol Stud 39:11–25

Imlay JA (2003) Pathways of oxidative damage. Ann Rev Microbiol 57:395–408

Jithesh MN, Prashanth SR, Sivaprakash KR, Parida AK (2006a) Antioxidative response mechanisms in halophytes: their role in stress defence. J Genet 85:237–254

Jithesh MN, Prashanth SR, Sivaprakash KR, Parida AK (2006b) Monitoring expression profiles of antioxidant genes to salinity, iron, oxidative, light and hyperosmotic stresses in the highly salt tolerant grey mangrove, *Avicennia marina* (Forsk.) Vierh by mRNA analysis. Plant Cell Rep 25:865–876

Jun W, Qiang X, Jing X, Min YL, Jian YP, Mei-hua Y (2008) Natural products from true mangrove flora: source, chemistry and bioactivities. Nat Prod Rep 25:955–981

Kanchanapoom T, Kasai R, Picheansoonthon C, Yamasaki K (2001) Megastigmane, aliphatic alcohol and benzoxazinoid glycosides from *Acanthus ebracteatus*. Phytochemistry 58:811–817

Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81–251

Khafagi I, Gab-Alla A, Salama W, Fouda M (2003) Biological activities and phytochemical constituents of the gray mangrove *Avicennia marina* (Forssk.) Vierh. Egyptian J Biol 5:62–69

Konishi T, Takasaki M, Tokuda H, Kiyosawa S, Konoshima T (1998) Anti-tumor promoting activity of diterpenes from *Excoecaria agallocha*. Bio Pharm Bull 21:993–996

Konishi T, Konoshima T, Fujiwara Y, Kiyosawa S (2000) Excoecarins D, E, and K, from *Excoecaria agallocha*. J Nat Prod 63:344–346

Krishnaiah D, Sarbatly R, Bono A (2007) Phytochemical antioxidants for health and medicine: a move towards nature. Biotechnol Mol Biol Rev 1:097–104

Krishnamoorthy M, Sasikumat JM, Shamna R, Pandirajan C, Sofia P, Nagarajan B (2011) Antioxidant activities of bark extract from mangroves, *Bruguiera cylindrica* (L.) Blume and *Ceriops decandra* Perr. Indian J Pharmacol 43:369–370

Ksouri R, Falleh H, Megdiche W, Trabelsi N, Mhamdi B, Chaieb K, Bakrouf A, Magne C, Abdelly C (2009) Antioxidant and antimicrobial activities of the edible medicinal halophyte *Tamarix gallica* L. and related polyphenolic constituents. Food Chem Toxicol 47:2083–2091

Li MY, Xiao Q, Pan JY, Wu J (2009) Review natural products from semi-mangrove flora: source, chemistry and bioactivities. Nat Prod Rep 26:281–298

Li YX, Yu X, Yu SJ, Ma AY, Deng ZW, Lin WH (2010) phenolic glucopyranosides from the Chinese mangrove plant *Excoecaria agallocha*. J Chin Pharm Sci 19:256–259

Liebezeit G, Rau MT (2006) New Guinean mangroves—traditional usage and chemistry of natural products. Sencken Mari 36:1–10

Lobreaux S, Thoiron S, Briat JF (1995) Induction of ferritin synthesis in maize leaves by an iron-mediated oxidative stress. Plant J 8:443–449

Loo AY, Jain K, Darah I (2008) Antioxidant activity of compounds isolated from the pyroligneous acid, *Rhizophora apiculata*. Food Chem 107:1151–1160

Mahajan S, Tuteja N (2005) Cold, salinity and drought stresses: an overview. Arch Biochem Biophys 444:139–158

Mallik S, Nayak M, Sahu BB, Panigrahi AK, Shaw BP (2011) Response of antioxidant enzymes to high NaCl concentration in different salt-tolerant plants. Biol Plant 55:191–195

Masuda T, Yonemori S, Oyama Y, Takeda Y, Tanaka T, Ando T, Shinohara A, Nakata M (1999) Evaluation of the antioxidant activity of environmental plants: activity of the leaf extracts from seashore plants. J Agri Food Chem 47:1749–1754

McDonald S, Prenzler PD, Antolovich M, Robards K (2001) Phenolic content and antioxidant activity of olive extracts. Food Chem 73:73–84

Milon MA (2012) Antioxidant, cytotoxic and antimicrobial activity of *Sonneratia alba* bark. Int J Pharm Sci Res 3:2233–2237

Mishra S, Das AB (2003) Effect of NaCl on leaf salt secretion and antioxidative enzyme level in roots of a mangrove, *Aegiceras corniculatum*. Indian J Exp Biol 41:160–166

Mittler R (2002) Oxidative stress, antioxidants and stress tolerance. Trends Plant Sci 7:405–410

Mittler R, Vanderauwera S, Gollery M, Van Breusegem F (2004) Reactive oxygen gene network of plants. Trends Plant Sci 9:490–498

Mullineaux PM, Rausch T (2005) Glutathione, photosynthesis and the redox regulation of stress-responsive gene expression. Photosynth Res 86:459–474

Noctor G, Foyer CH (1998) A re-evaluation of the ATP: NADPH budget during C3 photosynthesis. A contribution from nitrate assimilation and its associated respiratory activity. J Exp Bot 49:1895–1908

Oktay M, Gulcin I, Kufrevioglu OI (2003) Determination of in vitro antioxidant activity of fennel (*Foeniculum vulgare*) seed extracts. Leb Wissen Technol 36:263–271

Ospina LE, Calle J, Arteaga L, Pinzo NR, Alcaraz MJ, Ac Paya M (2001) Flavonol glycosides and novel iridoid glycoside from the leaves of *Morinda citrifolia*. Plant Med 67:791–795

Pandhair V, Sekhon BS (2006) Reactive oxygen species and antioxidant in plants—an overview. J Plant Biochem Biotechnol 15:71–78

Paramonova NV, Shevyakova NI, Kuznetsov VV (2004) Ultrastructure of chloroplasts and their storage inclusions in the primary leaves of *Mesembryanthemum crystallinum* affected by putrescine and NaCl. Russ J Plant Physiol 1:86–96

Parida AK, Jha B (2010) Salt tolerance mechanisms in mangroves: a review. Trees 24:199–217

Parida AK, Das AB, Mohanty P (2004) Investigations on the antioxidative defence responses to NaCl stress in a mangrove, *Bruguiera parviflora*: differential regulations of isoforms of some antioxidative enzymes. Plant Growth Regul 42:213–226

Patra JK, Thatoi HN (2011) Metabolic diversity and bioactivity screening of mangrove plants: a review. Acta Physiol Plant 33:1051–1061

Patra JK, Rath SK, Jena K, Rathod VK, Thatoi HN (2008) Evaluation of antioxidant and antimicrobial activity of seaweed (*Sargassum* sp.) extract: a study on inhibition of Glutathione-S-transferase activity. Turk J Biol 32:119–125

Patra JK, DasMohapatra A, Rath SK, Dhal NK, Thatoi HN (2009a) Screening of antioxidant and antimicrobial activity of leaf extracts of *Excoecaria agallocha* L. Int J Integr Biol 7:9–15

Patra JK, Panigrahi TK, Rath SK, Dhal NK, Thatoi HN (2009b) Phytochemical screening and antimicrobial assessment of leaf extracts of *Excoecaria agallocha* L.: a mangal species of Bhitarkanika, Orissa, India. Adv Nat Appl Sci 3:241–246

Patra JK, Dhal NK, Thatoi HN (2011) *In vitro* bioactivity and phytochemical screening of *Suaeda maritima* (Dumort): a mangrove associate from Bhitarkanika, India. Asian Pac J Trop Med 4:727–734

Pellegrini N, Serafini M, Colombi B, Del Rio D, Salvatore S (2003) Total antioxidant capacity of plant foods, beverages and oils consumed in Italy assessed by three different in vitro assays. J Nutr 133:2812–2819

Pisoschi AM, Negulescu GP (2011) Methods for total antioxidant activity determination: a review. Biochem Anal Biochem 1:1–10

Popov IN, Lewin G (1996) Photochemiluminescent detection of antiradical activity; IV: testing of lipid-soluble antioxidants. J Biochem Biophy Methods 31:1–8

Prabhu VV, Guruvayoorappan C (2012) Phytochemical screening of methanolic extract of mangrove *Avicennia marina* (Forssk.)Vierh. Der Pharmacia Sinica 3:64–70

Prieto P, Pineda M, Aguilar M (1999) Spectrophotometric quantitation of antioxidant capacity through the formation of a phosphomolybdenum complex: specific application to the determination of vitamin E. Anal Biochem 269:337–341

Rahim AA, Rocca E, Steinmetz J, Kassim MJ, Ibrahim MS, Osman H (2008) Antioxidant activities of mangrove *Rhizophora apiculata* bark extracts. Food Chem 107:200–207

Ramchoun M, Harnafi H, Alem C, Benlys M, Elrhaffari L, Amrani S (2009) Study on antioxidant and hypolipidemic effects of polyphenol rich extract from *Thymus vulgaris* and *Lavandula multifida*. Pharmacogn Res 1:106–112

Ravikumar S, Gnanadesigan M (2011a) Hepatoprotective and antioxidant activity of a mangrove plant *Lumnitzera* racemosa. Asian Pac J Trop Biomed 1(5):348–352

Ravikumar S, Gnanadesigan M (2011b) Hepatoprotective and antioxidant properties of Rhizophora mucronata mangrove plant in CCl4 intoxicated rats. J Exp Clin Med 4:66–72

Ravikumar S, Gnanadesigan M, Inbaneson SJ, Kalaiarasi A (2011) Hepatoprotective and antioxidant properties of Suaeda maritima (L.) Dumort ethanolic extract on concanvalin-A induced hepatotoxicity in rats. Indian J Exp Biol 49:455–460

Ravindran C, Naveenan T, Varatharajan GR, Rajasabapathy R, Meena RM (2012) Antioxidants in mangrove plants and endophytic fungal associations. Bot Mar 55:269–279

Rhodes D, Hanson AD (1993) Quaternary ammonium and tertiary sulfonium compounds in higher-plants. Ann Rev Plant Physiol Plant Mol Biol 44:357–384

Roome T, Dar A, Ali S, Naqvi S, Choudhary MI (2008) A study on antioxidant, free radical scavenging, anti-inflammatory and hepatoprotective actions of *Aegiceras corniculatum* (stem) extracts. J Ethnopharmacol 118:514–521

Ru QM, Xiao Q, Lin P, Pei ZM, Zheng HL (2009) Short- and long-term effects of NaCl on physiological and biochemical characteristics in leaves of a true mangrove, *Kandelia candel*. Russ J Plant Physiol 56:3363–3369

Salekdeh GH, Siopongco J, Wade LJ, Ghareyazie B, Bennett J (2002) A proteomic approach to analyzing drought- and salt-responsiveness in rice. Field Crop Res 76:199–219

Scandalios JG (1993) Oxygen stress and superoxide dismutases. Plant Physiol 101:7–12

Schwarzländer M, Fricker MD, Marty CM, Brach L, Novak T, Sweetlove J, Meyer AJ (2008) Confocal imaging of glutathione redox potential in living plant cells. J Microbiol 231:299–316

Selvakumar K, Madhan R, Srinivasan G, Baskar V (2011) Antioxidant assays in pharmacological research. Asian J Pharm Tech 1:99–103

Serafini M, Del Rio D (2004) Understanding the association between dietary antioxidants, redox status and disease: is the total antioxidant capacity the right tool? Redox Rep 9:145–152

Shanmugapriya R, Ramanathan T, Renugadevi G (2012) Phytochemical characterization and antimicrobial efficiency of mangrove plants *Avicennia marina* and *Avicennia officinalis*. Int J Pharm Biol Arch 3:348–351

Shi H, Ishitani M, Kim C, Zhu JK (2000) The Arabidopsis thaliana salt tolerance gene SOS1 encodes a putative Na^+/H^+ antiporter. Proc Nat Acad Sci 97:6896–6901

Shi C, Xu MJ, Bayer M, Deng ZW, Kubbutat MHG, Waejen W, Proksch P, Lin WH (2010) Phenolic compounds and their antioxidative properties and protein kinase inhibition from the Chinese mangrove plant *Laguncularia racemosa*. Phytochemistry 71:435–442

Singh A, Duggal S, Suttee A (2009) *Acanthus ilicifolius* linn.-lesser known medicinal plants with significant pharmacological activities. Int J Phytomed 1:1–3

Slavíková H, Lojek A, Hamar J, Dušková M, Kubala L (1998) Total antioxidant capacity of serum increased in early but not in late period after intestinal ischemia in rats. Free Radic Biol Med 25:9–18

Soler-Rivas C, Espin JC, Wichers HJ (2000) An easy and fast test to compare total free radical scavenger capacity of foodstuffs. Phytochem Anal 11:330–338

Subhan N, Alam MA, Ahmed F, Awal MA, Nahar L, Sarker SD (2008) *In vitro* antioxidant property of the extract of *Excoecaria agallocha* (Euphorbiaceae). DARU 16:149–154

Suganthy N, Kesika P, Pandian SK, Devi KP (2009) Mangrove plants extract: radical scavenging activities and its battle against food borne pathogens. Forsch Komplementmed 16:41–48

Sun Y, Ding Y, Lin WH (2009) Isolation and identification of compounds from marine mangrove plant *Avicennia marina*. Beijing Da Xue Xue Bao 41:221–225

Takara K, Kuniyoshi A, Wada K, Kinjyo K, Iwasaki H (2008) Antioxidative flavan-3-ol glycosides from stems of *Rhizophora stylosa*. Biosci Biotechnol Biochem 72:2191–2194

Takemura T, Hanagata N, Sugihara K, Baba S, Karube I, Dubinsky Z (2000) Physiological and biochemical responses to salt stress in the mangrove, *Bruguiera gymnorrhiza*. Aquatic Bot 68:15–28

Takemura T, Hanagata N, Dubinsky Z, Karube I (2002) Molecular characterization and response to salt stress of mRNAs encoding cytosolic Cu/Zn superoxide dismutase and catalase from *Bruguiera gymnorrhiza*. Trees Struct Funct 16:94–99

Thaipong K, Boonprakob U, Crosby K, Cisneros-Zevallos L, Byrne DH (2006) Comparison of ABTS, DPPH, FRAP, and ORAC assays for estimating antioxidant activity from guava fruit extracts. J Food Comp Anal 19:669–675

Theil EC (1987) Ferritin: structure, gene regulation, and cellular function in animals, plants and microorganisms. Annu Rev Biochem 56:289–315

Thirunavukkarasu P, Ramanathan T, Ramkumar L, Shanmugapriya R, Renugadevi G (2011a) The antioxidant and free radical scavenging effect of *Avicennia officinalis*. J Med Plants Res 5:4754–4758

Thirunavukkarasu P, Ramanathan T, Shanmugapriya R, Umamaheswari G, Renugadevi G (2011b) Antioxidant and free radical scavenging effect of *Acanthus ilicifolius*. Res J Appl Sci 6:218–222

Vadlapudi V, Naidu KC (2009) Evaluation of antioxidant potential of selected mangrove plants. J Pharm Res 2:1742–1745

Wagner D, Przybyla D, Opden Camp R, Kim C, Landgraf F, Lee KP, Wursch M, Laloi C, Nater M, Hideg E, Apel K (2004) The genetic basis of singlet oxygen induced stress responses of *Arabidopsis thaliana*. Science 306:1183–1185

Wang B, Luttge U, Ratajczak R (2004) Specific regulation of SOD isoforms by NaCl and osmotic stress in leaves of the C3 halophyte *Suaeda salsa* L. J Plant Physiol 161:285–293

Wangensteen H, Dang HCT, Uddin SJ, Alamgir M, Malterud KE (2009) Antioxidant and antimicrobial effects of the mangrove tree *Heritiera fomes*. Nat Prod Commun 4:371–376

Wei SD, Chen RY, Liao MM, Tu N, Zhou HC, Lin YM (2011) Antioxidant condensed tannins from *Machilus pauhoi* leaves. J Med Plants Res 5:796–804

Willekens H, Inze D, Van Montagu M, Van Camp W (1995) Catalase in plants. Mol Breed 1:207–208

Xiang C, Werner BL, Christensen EM, Oliver DJ (2001) The biological functions of glutathione revisited in *Arabidopsis* transgenic plants with altered glutathione levels. Plant Physiol 126:564–574

Yen GC, Chen HY (1995) Antioxidant activity of various tea extracts in relation to their antimutagenicity. J Agri Food Chem 43:27–32

Zhang LL, Lin YM, Zhou HC, Wei SD, Chen JH (2010) Condensed tannins from mangrove species *Kandelia candel* and *Rhizophora mangle* and their antioxidant activity. Molecules 15:420–431

Zhu F, Chen X, Yuan Y, Huang M, Sun H, Xiang W (2009) The chemical investigations of the mangrove plant *Avicennia marina* and its endophytes. Open Nat Prod J 2:24–32