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A review of plant metabolites with metal interaction capacity: a green approach for industrial applications

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Abstract Rapid industrial development is responsible for severe problems related to environmental pollution. Many human and industrial activities require different metals and, as a result, great amounts of metals/heavy metals are discharged into the water and soil making them dangerous for both human and ecosystems and this is being aggravated by intensive demand and utilization. In addition, compounds with metal binding capacities are needed to be used for several purposes including in activities related to the removal and/or recovery of metals from effluents and soils, as metals' corrosion inhibitors, in the synthesis of metallic nanoparticles and as metal related pharmaceuticals, preferably a with minimum risks associated to the environment. Plants are able to synthesize an uncountable number of compounds with numerous functions, including compounds with metal binding capabilities. In fact, some of the plants' secondary metabolites can bind to various metals through different mechanisms, as such they are excellent sources of such compounds due to their high availability and vast diversity. In addition, the use of plant-based compounds is desirable from an environmental and economical point of view, thus being potential candidates for utilization in different industrial activities, replacing conventional physiochemical methods. This review focuses on the ability of some classes of compounds that can be found in relatively high concentrations in plants, having good metal binding capacities and thus with potential utilization in metal based industrial activities and that can be involved in the progressive development of new environmentally friendly strategies.

Keywords Active plant-based compounds · Secondary metabolites · Metal binding · Metal interaction · Industrial applications

Introduction

Metals are pivotal in the global economy as key constituents of a vast number of products and industrial processes enabling our core societal and industrial activities from electronic devices, vehicle production, constructions to agriculture and medicine. Each metal and its alloys have unique properties that make them interesting for different applications. Currently, the majority of metals are obtained from primary sources, which have critically limited sources and disparately spread worldwide. In the last centuries, as a result of rapid industrialization and population explosion,

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Table 1 Some examples of recent applications of plants compounds with metal interaction potential

Application	Plant	Reported compound	Target metal/ metal compound	Reference
Metal insolubilization	*Olea europaea* and *Citrus aurantium*	Saponins	Pb^{2+}, Cd^{2+}	(Abed el Aziz et al. 2017)
	Spinach, Coffee, and Tea	Plyphenols, Alkaloids (Not specified)	Pb^{2+}	(Lathan et al. 2013)
	Ocimum gratissimum	Flavonoid	Ni^{2+}, Zn^{2+}, Cu^{2+}	(Louis et al. 2018)
	Acacia nilotica	Tannins	Ni^{2+}	(Meethale Kunnambath and Thirumalaisamy 2015)
Nanoparticle synthesis	*Oldenlandia corymbosa* L.	Alkaloids, Saponins, Polyphenols, and Flavonoids	CuO	(Yulizar et al. 2018)
	Ginkgo biloba	Polysaccharide	Pd^{2+}	(Cui et al. 2020)
	Salvadora persica	Polyphenols	Pd^{2+}	(Khan et al. 2017)
	Trianthema portulacastrum and *Chenopodium quinoa*	Not reported	TiO_2	(Irshad et al. 2020)
	Oscillatoria limnetica	Free amino groups, sulfur containing amino acid derivatives	Ag^{+}	(Hamouda et al. 2019)
	Andrographis paniculata	Terpenoids	ZnO	(Kavitha et al. 2017)
	Black tea	Polyphenols, Flavonoids	Au^{3+}	(Alegria et al. 2018)
	Azadirachta indica	Carbonyls, alkanes and aliphatic amines,	Pt^{4+}	(Thirumurugan et al. 2016)
Corrosion inhibitor	*Myrtus communis*	Limonene, linalool, pinene, 1,8-cineole, linanyl acetate, and terpineol (Not specified)	Copper	(Bozorg et al. 2014)
	Corchorus olitorius	(Not specified) mixed-type inhibitor	Mild steel	(Gobara et al. 2017)
	Sapium ellipticum	lavonoids, phenolics, alkaloids, tannins, terpenoids, steroids	Aluminum	(Okechukwu Dominic et al. 2020)
	Tridax procumbens and *Chromolaena odorata*	Flavanones, Persicogenin, Chalcones, Flavones and Luteoli (Not specified)	Stainless steel	(Aribo et al. 2017)
Biosorption	*Lagestroemia speciosa*	Tannin	Pd^{2+}	(Choudhary et al. 2017)
	Cladophora glomerate (Algae)	Not reported	Cr^{6+}	(Al-Homaidan et al. 2018)
	Walnut Shells	Polysaccharides	Heavy metals	(Halysh et al. 2020)
	Rhizopus sp. (Fungi)	Not reported	Cu^{2+}	(Gomes et al. 2014)
	Banana peel	Compounds with nitrogen, sulfur, and carboxylic acids are responsible	Pb^{2+}, Cu^{2+}	(Kok Seng 2018)

metal extraction from primary sources has tremendously increased, leading to a significant depletion of these resources. As a consequence, the necessity of resourcing metals from secondary sources by employing environmentally friendly and sustainable technologies has been emerging.

Plants are valuable resources for all living organisms existing on our planet and have evolved to survive in soils containing very low available metals (Morales et al. 2018), while others have lived in habitats with high heavy metal contents. As a result, they have developed strategies for metal uptake (micronutrients) and delivery from roots to different parts of the plant (González-Guerrero et al. 2016) benefiting from different active phytochemicals. They have also developed mechanisms to overcome the toxicity of heavy metals in their growing bed, which include exclusion, inactivation and organic ligands exudation (Choppala et al. 2014). As an example, different plants like coffee, green tea and vegetables (-like spinach) are rich in different types of polyphenols, gallic acid and many other bioactive compounds (McDonald et al. 1996; Chaturvedula and Prakash 2011; Cvjetko Bubalo et al. 2018) that have different roles in plant and metal-interaction characteristics. Generally, different parts of the plant may contain distinct active ingredients. These renewable resources provide raw materials and phytochemicals, notably secondary metabolites like alkaloids, flavonoids, tannins, phenolic acids, saponins, steroids, etc., with many different mechanisms of interaction with metals that can be used for different industrial purposes. For instance, phenolic compounds have several roles in different parts of the plant, such as providing more support for the plant's structural system, protection against herbivores, pathogens, harmful solar radiations (e.g. UV) etc. (de la Rosa et al. 2019), but because of their special structure, they are also capable metal chelators (Rahim et al. 2019).

It is well-known that molecules containing atoms with lone-pair electrons, such as oxygen, nitrogen and sulfur are frequently used to interact with metals in different hydrometallurgical processes involving metal solubilization (e.g., leaching processes), extraction (e.g., liquid-liquid and solid-liquid extraction processes) and removal (e.g., via the use of sorbent materials). Hence, the search and extraction of natural compounds containing those groups of atoms from plants can be determinant to develop green and more environmentally friendly industrial processes. Plant active compounds, depending on their nature, contain polar functional groups, such as carboxyl, phenolic, hydroxyl, sulfo and amino groups that are capable of interacting with metal ions through different mechanisms such as complex/chelate formation (Mejáre and Bülow 2001; Clemens 2001; Ma et al. 2016), reduction (Sharma et al. 1998; Ma et al. 2016; Ishak et al. 2019), ion exchange (Gurung et al. 2013; Anjum et al. 2015; Li et al. 2017), sorption (Pietrobelli et al. 2009; Akpomie et al. 2015), electrostatic attraction (Yermiyahu and Kinraide 2005), covalent binding (Anjum et al. 2015), van der Waals attraction (Pietrobelli et al. 2009) and precipitation (Pietrobelli et al. 2009; Ma et al. 2016).

These compounds with desired metal interaction properties, can be used as an alternative to conventional methods in different applications relating to metals as they are renewable, eco-friendly and based on low-cost materials. They have potential to be used in different metal related industrial applications like metallic nanoparticle synthesis, metal related pharmaceuticals, metals' corrosion inhibitors, wastewater treatment, metal recovery, etc. (Table 1). The attempt to use plant based-compounds for metal recovery or removal from contaminated waters/wastewaters is a new and very promising topic, aiming the development of greener technologies in alternative to the traditional ones (chemical precipitation, ion exchange, and electrochemical removal) which are frequently non-environmentally friendly and not suitable to be applied for metal recovery from low grade minerals and secondary sources.

In the present review, the emphasis is on the most important variety of molecules of plant secondary metabolites reported as capable of specific

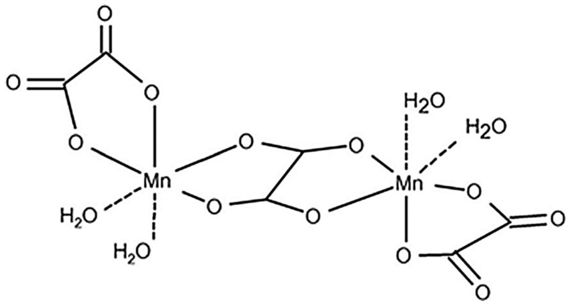

Fig. 1 Schematic view of the Mn(II) complexes with oxalate (Baran 2014)

metal(s) interaction, aiming to offer an overview of the many possible fields of application of these compounds in research, industry and health.

Plant metabolites with metal interaction potential

Organic acids

Organic acids are organic compounds possessing the carboxyl group (R-COOH) which has acidic characteristics usually associated to their ability to donate protons to water molecules (Brønsted-Lowry theory), in what is called dissociation reactions. Acids are classified as strong, if the reaction with the solvent is sufficiently complete leading to no undissociated solute molecules in the solution. Otherwise, if a partial dissociation occurs, which is the most frequent situation within organic acids, they are classified as weak, which means they react incompletely with water producing solutions containing both the parent acid and its conjugate. Different organic acids such as citric, oxalic, malic, malonic, aconitic and tartaric acids, possess at least one carboxyl group, that after losing their proton may act as oxygen-electron donor ligands (Anjum et al. 2015), thus reacting with metals and forming complexes and chelates. Organic acids possess varying negative charges (due to the dissociation degree of the carboxylic groups depending on the medium pH) responsible for complex formation with many different metal ions in the solutions.

It has been argued that organic acids complexation with metals plays a vital role in transporting the heavy metals from roots to shoots (Rascio and Navari-Izzo 2011). For instance, citrate has a strong metal ion chelation, especially in the case of Fe^{2+} (Clemens 2001), Al^{3+} (Ownby and Popham 1990), Ni^{2+} (Ferrero et al. 2020) and Zn^{2+} (Godbold et al. 1984). Also, there are works reporting that citrate has a high affinity for other metals like Zn, Ni, Cd, and Co (Anjum et al. 2015). Higher amounts of citrate is found in different plants like in spinach leaves, *Lemons* and wild strawberries, containing about 8 to 15% citrate of their dried weight (Popova and Pinheiro de Carvalho 1998).

Oxalate is the smallest organic dicarboxylate ligand among low molar mass organic compounds and is also one of the most abundant low molar mass organic acids in nature (Strobel 2001). It is present in relatively low amounts in most of plants but it can be found in elevated concentrations in some extreme oxalate accumulator varieties (about > 3–80% oxalate (w/w) of plants' dried weight) (Libert and Franceschi 1987) from the families of *Agavaceae*, *Aizoaceae*, *Amaranthaceae*, *Araceae*, *Cactaceae*, *Euphorbiaceae*, *Fabaceae*, *Oxalidaceaea*, *Polygonaceae* and *Poaceae* (Reyers and Naude 2012). The oxalate anion is an extensively investigated and well known ligand, capable of generating expansive varieties of complexes and salts with most of the metal oxides and bases (Cotton and Cotton 1999). As oxalate can act in the form of mono-, bi-, tri- and tetradentate ligand, it has the potential to form mononuclear and polynuclear metal complexes (Fig. 1) (Baran 2014). There are many more oxalate metal (such as Mg(II), Fe(II), Zn(II), Co(II), Ni(II) and Mn(II)) complexes reported by Baran (2014). In plants, as implied by Çalişkan (2000), oxalate has an important role in balancing the high concentration of cations (like Na^+, Ca^{2+} and $NH^+{}_4$) over anions (like Cl^-, $H_2PO^-{}_4$ and $NO^-{}_3$).

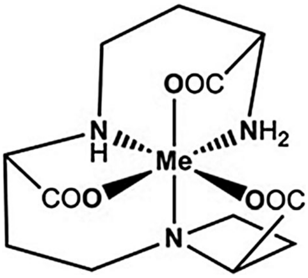

Fig. 2 Structure of nicotamine-metal complex (Kutrowska and Szelag 2014)

Amino acids

Amino acids are a type of organic acids that contain amine and carboxyl groups coupled with particular side chains for each amino acid (Nelson and Cox 2005). These molecules have been found throughout the life science and vary tremendously in their function and complexity. Amino acids and their derivatives are compounds with metal interaction capabilities, cheap and soluble in aqueous media. These features, make them an essential part in elevating plant tolerance through metal stress. Unfortunately, the literature is scare on information regarding the mechanism of metal chelation by these compounds.

There are studies suggesting that these compounds may form five membered chelates with different metals through their amine and carboxylate groups (*N*, *O*-chelation) (Laurie 1995). They may also have other metal binding sites on the side chain of their molecules, making them able to interact with a variety of metals. Groups such as the imidazole ring (a planar 5-membered ring with the general formula of 1,3-C_3N_2) of histidine, the phenol ring of tyrosine, the β- and γ-carboxylate groups in glutamate and aspartate, the thiol group (R-SH) of cysteine and the thioether moiety (R-S-R) of methionine are often the important metal binding sites in amino acids (Laurie 1995).

Betaine is a quaternion ammonium compound containing a group of carboxylic acid. Among various types of this amino acid, glycine betaine is the most common. The role of the glycine betaine in the plants exposed to high levels of metals has been reported to be as a metal chelator, osmoprotectant and reactive oxygen species scavenger (Gill et al. 2014; Hossain et al. 2015; Ali et al. 2020).

There is not sufficient information in the literature regarding the metal specificity of amino acids and their derivatives. In plants, compounds like proline and glutamic acid, nicotianamine (non-protein amino acid) and polyamines play a major role in metal detoxification and chelation (Hasanuzzaman and Fujita 2013; Anjum et al. 2015; Delangiz et al. 2020). For example, in copper deficiency and excess conditions, nicotianamine, proline and histidine are reported to have a critical role in copper chelation in xylem sap of *Brassica carinata* (Irtelli et al. 2009). Besides metal binding capacities, proline and histidine are known to be accumulated and act as signaling and antioxidant agents in the plants exposed to heavy metals (e.g., Cd, Ni and Cu) (Richau and Schat 2009; Anjum et al. 2013; Gill et al. 2014). Histidine, as an important nitrogen donor ligand, is a crucial compound in metal accumulator plants such as *Alyssum lesbiacum* (Krämer et al. 1996). Histidine is considered as an important metal chelator in plants through its amino, carboxyl and imidazole functional groups (Anjum et al. 2015; Seregin and Kozhevnikova 2020). Its metal chelation role in plants exposed to various metals is reported by many researchers (Richau and Schat 2009; Richau et al. 2009; Monsant et al. 2011; Seregin and Kozhevnikova 2020).

The non-proteinogenous amino acid nicotianamine is a vital component of plant metal assimilation and a homeostasis as it is a capable metal chelator; it has a key role in uptake, phloem transport and cytoplasmic distribution (Agnihotri and Seth 2019). Literature provides evidence regarding the accumulation of nicotianamine in plants upon exposure to different metals specially Zn, Cu, Fe, Ni and Cd (Irtelli et al. 2009; Mehes-Smith et al. 2013; Chen et al. 2018). The presence of six functional groups gives nicotianamine its octahedral coordination and potential for the chelation of different metals (Fig. 2) (Rellán-Álvarez et al. 2008). Finally, the pK of the metal-nicotianamine complexes along with the pH of the solution were considered to control the chelation ability of nicotianamine (Rellán-Álvarez et al. 2008).

Amino acids can also be used to synthesize other compounds with metal chelating ability; for instance, deoxyalliin (S-allyl-L-cysteine) is one of the cysteine derivatives with vegetal origination. Deoxyalliin is a strong ligand with the ability to synthesize compounds with bioactive metals such as Cu, Ni, Fe and Co (Massabni et al. 2005).

Proteins

Proteins are large natural molecules composed of one or more chains of amino acids in a specific order. They interact with different metal ions and therefore, these interactions play an important role in biological systems. Plant waste (such as soybean, corn etc.) and

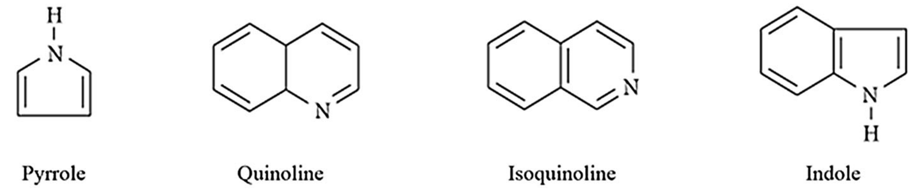

Fig. 3 Typical basic structure of alkaloids (Achilonu and Umesiobi 2015)

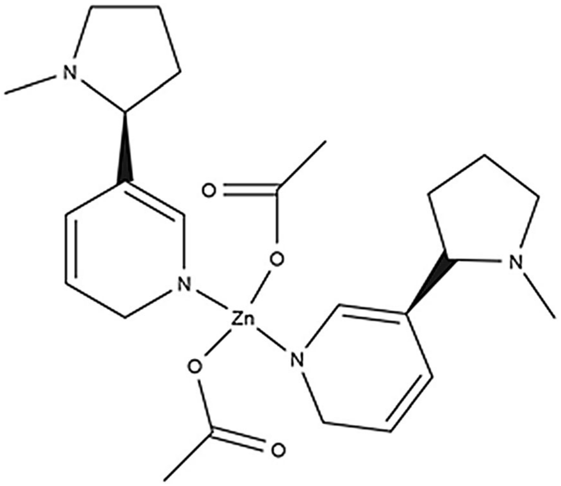

Fig. 4 Structure of zinc-nicotine complex (Mahmood et al. 2018)

waste from agricultural industries are often composed of protein-rich biomass, a part of which has been used as a source of peptides and amino acids. For example, calmodulin that can be found in plants like *Arabidopsis thaliana*, *Oryza sativa*, *Nicotiana tabacum*, *Medicago truncatula*, *Glycine max*, etc. (Ranty et al. 2006) is a calcium-binding protein (with two domains, each domain contains two Ca^{2+} binding sites) which is present in both apo- and holo-form in plant cells (Chin and Means 2000).

Moreover, among protein-based metal chelators, metallothioneins are an important class. Metallothioneins possess a thiol group (–SH group) being S- an electron donor ligand. They have low mass weight and are Cystein-rich metal-binding proteins (Cysteine (*Cys*) is a semi essential proteinogenic amino acid with a thiol side) that are distributed in prokaryotic and eukaryotic organisms and according to the arrangement of *Cys* residues are classified as Class I and II (Cobbett and Goldsbrough 2002). All the plant metallothioneins are in Class II and typically contain two *Cys*-rich metal binding domains in carboxy- and amino- terminal regions (Cobbett and Goldsbrough 2002). Covalent binding of metal atoms involves sulfhydryl cysteine residues. The C-terminal part (the α-domain) can bind to the four divalent metal ions, while the N-terminal part of the peptide is designated as β-domain and has three binding sites for divalent metal ions (Ruttkay-Nedecky et al. 2013). A principal feature of metallothionein complexes with metal ions is the co-occurrence of low kinetics and high thermodynamics, resulting on a tight metal complexation along with the high availability of a part of metals for other proteins (Hassinen et al. 2011). Compounds from the metallothioneins family are a wide range of small *Cys*-rich proteins, with the potential of binding transitional metal ions such as Cd^{2+}, Cu^{+} and Zn^{2+} (Freisinger 2011; Leszczyszyn et al. 2013). Additionally, proteins are able to adsorb precious metal ions such as Au^{3+}, Pd^{2+} and Pt^{4+} (Maruyama et al. 2007) because of the strong and specific interactions between precious metal ions and proteins (Zou et al. 2000).

Alkaloids

Among the plants' secondary metabolites, alkaloids are one of the biggest groups that are found in about 20% of plant species. They are low molecular weight compounds and are generally alkaline due to the presence of a nitrogen atom in their heterocyclic ring (Fig. 3). Indeed, the properties of alkaloids are highly affected by the precise position of N atom. The low distribution of these compounds in the living organisms is due to their negatively charged nitrogen (Pelletier 1996). Alkaloids are divided into more than 20 classes like piperidine, pyridine, pyrrolidine, tropane etc. (Yang and Stöckigt 2010; Debnath et al. 2018). Some higher plants in the families of *Papaveraceae*, *Berberidaceae*, *Fabaceae*, *Boraginaceae*, *Apocynaceae*, *Asclepiadaceae*, *Asteraceae*, *Liliaceae*, *Gnetaceae*, *Ranunculaceae*, *Rubiaceae*, *Solanaceae*, and *Rutaceae* contain high levels of alkaloids (Wink 2003). Most of these compounds can be extracted and purified through acid-base extraction, although DESs (Deep Eutectic Solvents), as a green solvent, may also be applied for the alkaloid extraction (Jiang et al. 2019).

There are reports indicating that many alkaloids can form complexes with different metals which is the case of xanthine-based alkaloids (like caffeine) (Umaley and Aswar 2015), pyridine group alkaloids like nicotine (Fazary et al. 2017), cinchona (quinoline group) (Boratyński et al. 2019), sparteine (quinolizidine group) (Jasiewicz 2009), quinoline derivatives (DiMauro et al. 2003) and isoquinoline derivatives (like berberine) (Khan et al. 2019; Neag et al. 2018) etc.

Berberine is an alkaloid from the protoberberine group of benzylisoquinoline alkaloids. Mechanisms

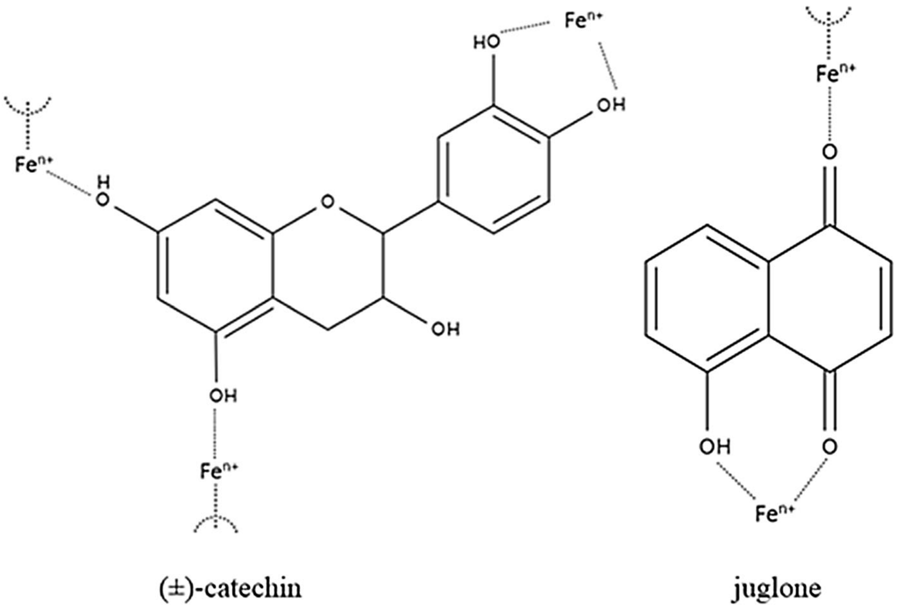

Fig. 5 A schematic view of iron chelation by two different phenolic compounds, (±)-catechin and juglone (Chobot and Hadacek 2010)

associated to its antioxidant capacity, may not only induce their metal binding potential, but can also cause an improvement in the antioxidant activity of some other endogenous compounds, like the elimination of free oxygen, oxidation of certain compounds and minimization of the destructivity of superoxide ions (Neag et al. 2018). Its antioxidant capacity is comparable with vitamin C, which is a capable antioxidant (Ahmed et al. 2015). Cinchona alkaloids are polytopic ligands capable of forming various types of complexes with many metal ions such as Pd(II), Co(III), Cu(II) etc. (Boratyński et al. 2019). Figure 4 presents the suggested structure of Zn-nicotine complex (Mahmood et al. 2018).

Besides the deep influence of sparteine and its isomers as chiral ligands in asymmetric synthesis, namely in organolithium chemistry, these have been used as ligands to form complexes with metals such as Pd, Cu and Zn (Maheswaran et al. 2006). Moreover, complexes of the sparteine-Cu(II) have been applied as a representative substance for type I copper(II) site of blue copper protein (Kim et al. 2001). A study revealed that root extract of *Ipomoea pes-caprae* rich in different classes of alkaloids such as indolizidines, ergolines and benzenoids, reduces Ag(I) to Ag(0) and effectively stabilizes the formed silver nanoparticles (Subha et al. 2015). There are many applications of alkaloids due to their ability to bond to metal ions. For instance, different types of alkaloids have been reported to be utilized as corrosion inhibitors of various metals (Li et al. 2019).

Phenols

Phenolic compounds are mainly distinguished by the hexagonal aromatic ring bonded directly to at least one (phenol) or more (polyphenol) hydroxyl groups (–OH) and other substituents, such as methoxyl or carboxyl groups, which are responsible for the polar character of these compounds and allow their dissolution in water (Michalak 2006). They are separated into numerous diverse groups and are characterized by the number of comprised carbon atoms bonded to the main phenolic structure such as phenolic acids, flavonoids, stilbenes, coumarins, hydrolysable tannins, monolignols, lignans and lignins (Cheynier et al. 2013). Phenolic compounds are one of the most important group of secondary metabolites synthesized by plants. They comprise 0.5–5% of plants' dry weight (Swanson 2003) and are present in different plants and their wastes. They can be found in high concentrations in apple peel and flesh (Chen et al. 2012), tomato wastes (Ćetković et al. 2012), black, green and Australian fresh tea (Yao et al. 2004), spinach

(Manach et al. 2004), chestnuts (flower, skin leaf and fruit) (Barreira et al. 2008), olives (Seabra et al. 2010) and in many other plants.

Phenols have an extensive application in many industrial sectors including agricultural, pharmaceutical and petrochemical industries, pesticide and food manufacturing and iron smelters. (Stefanakis and Thullner 2016). Their functional groups provide significant capacity in scavenging free radicals, as well as hydrogen atoms or electrons donation, which is determinant for their metal ions chelating capability (Kaurinovic and Vastag 2019). However, Kulbat (2016) showed that these valuable properties of phenols can also be due to the presence of nucleophilic aromatic rings in conjunction with the occurrence of definite functional groups such as carboxyl, hydroxyl and carbonyl groups, making them able to bind to different metals (Liu et al. 2018). This ability is important for the plants, since phenols enhance nutrient uptake by forming chelates with metal ions and promotes soil porosity and active absorption sites with accelerated mobilization of different metals such as iron, zinc, calcium, magnesium, potassium and manganese (Seneviratne and Jayasinghearachchi 2003). Chobot and Hadacek (2010) for example, were able to synthesize complexes of iron ions using phenolic secondary metabolites extracted from plants, such as (±)-catechin and juglone as shown in Fig. 5.

Moreover, some other works suggest that peroxidases and phenolic compounds in plants are involved in some defense reactions against oxidative stress mediated by copper ions (Posmyk et al. 2009). Studies imply that in many plants exposed to heavy metals, high levels of phenolics are secreted by the roots (Kováčik et al. 2010; Mongkhonsin et al. 2016). To reveal the interaction of these phenolic compounds with heavy metals, Lavid et al. (2001) extracted phenols from the rhizome of *Nympheae* and reported that the extracted phenols can directly bind and inactivate heavy metals such as Hg(II), Pb(II) and Cr(VI).

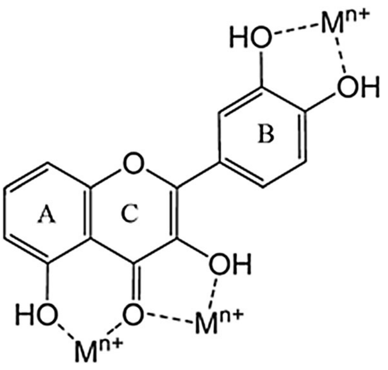

Fig. 6 Typical metal (M) chelation sites in flavonols (Pietta 2000)

Furthermore, phenolic compounds have antioxidant properties and ability to quench free radical reactions (Bozin et al. 2008) in a number of ways. They are involved in reactions with reactive oxygen and nitrogen species in a termination reaction and are also capable hydrogen donors, preventing new radical generation (Keerthana et al. 2019). Importantly, phenol antioxidant capacity is also attributed to their chelating ability of metal ions associated with the generation of free radicals (Yang et al. 2001). There is also another mechanism described as responsible for the antioxidant ability of phenols. Milić et al. (1998) mentioned that lipid hydroperoxide (LOOH) can be decomposed by metal ions' reaction leading to the hemolytic cleavage of the O–O bond, originating lipid alkoxyl radicals, which start free radical chain oxidation. Therefore, by trapping the lipid alkoxyl radical, phenolic antioxidants inhibit lipid peroxidation which relies on the phenol's structure, total number and precise position of the hydroxyl groups in their molecule (Milić et al. 1998).

The most common extraction procedures that have been used in extraction and isolation of phenolic compounds from plants are liquid-liquid extraction (Garcia-Salas et al. 2010), microwave-assisted extraction (Zin et al. 2020), supercritical fluid extraction (Tyśkiewicz et al. 2018) and ultrasound-assisted extraction (Medina-Torres et al. 2017). Most suitable solvents for polyphenol extraction from plants are aqueous mixtures with polar solvents including acetone (Park et al. 2014), ethanol (Taamalli et al. 2012), methanol (Dzah et al. 2020) and ethyl acetate (Castro-Vargas et al. 2010). Ethanol is a very efficient solvent for polyphenol extraction and is not hazardous for either human or the environment. On the other hand, low molecular weight polyphenols are extracted more effectively by methanol. Aqueous acetone is a favorable solvent for high molecular weight flavanols' extraction (Do et al. 2014). Ionic liquids (ILs) and DES have been proposed as a greener alternative to the common solvents and have gained more attention in various applications, including plant extract preparation. ILs are a combination of organic salts with low melting point and organic cations along with organic or inorganic anions. Unlike volatile organic solvents, ILs have very unique characteristics like good dissolving and extracting ability, high thermal stability, negligible vapor pressure, very wide liquidus range, good microwave absorbing ability and designable structures (Hoffmann et al. 2003; van Rantwijk and Sheldon 2007). ILs are efficient extractants of compounds with various polarities such as phenols (Du et al. 2009), alkaloids (Lu et al. 2008), organic acids (Absalan et al. 2008) and amino acids (Tang et al. 2010) from aqueous solutions. The application of ILs in association with other extraction techniques, namely ultrasonic treatment (Fan et al. 2012) and microwave (Swatloski et al. 2002) has been suggested for a more successful extraction of diverse kinds of natural compounds from solid materials such as plant biomass.

A novel class of solvents are Deep Eutectic Solvents (DES), which are prepared by combining two inexpensive and safe solid compounds (not essentially salts), such as sugars, choline and chloride with a much lower melting point than that of each of their components (Abbott et al. 2004). They have been recently used for the separation and extraction of bioactive compounds like phenols, alkaloids, flavonoids and catechins from plants (Cvjetko Bubalo et al. 2018; Huang et al. 2017; Jiang et al. 2019; Qi et al. 2015). Most of the DESs present advantages over conventional extractants such as ease of synthesis, safety, low-cost. They are also reported as energy efficient, recyclable, biodegradable and having negligible volatility at room temperature (Khandelwal et al. 2016), which are, in addition, important features. Many recent studies have applied DES and natural deep eutectic solvents (NDES) for the extraction of bioactive compounds from plants including alkaloids, flavonoids, phenols and catechins (Cvjetko Bubalo et al. 2018; Huang et al. 2017; Jiang et al. 2019; Qi et al. 2015).

Flavonoids

Flavonoids are derivatives of simple phenols with a general chemical structure based on 15-carbon skeleton (Fig. 6) consisting of two phenyl rings (A and B) and a heterocyclic ring (C) (Scotti et al. 2011). Flavonoids are one of the major group of plant secondary metabolites and it is estimated that almost 2% of photosynthesized carbon by plants is used for the synthesis of these compounds or related substances (Robards and Antolovich 1997). Until now, more than 8000 flavonoid compounds have been identified (Yan et al. 2020). In plants, the synthesis of flavonoids is reported to increase under the microbial infection, injury, decrease in temperature and deficiency of nutrients (Michalak 2006). This class of phenolic compounds are extensively distributed in all plants and exist mainly in higher concentrations in photosynthesizing cells. Different types of flavonoids can be found in high contents in tea (López et al. 2001) and families of *Asphodelaceae* and *Euphorbiaceae* (Lopez-Lazaro 2009), *Tiliaceae*, *Leguminosae* and *Compositae* (Gupta et al. 1983), *Mimosoideae* and *Bignoniaceaea* (Sannomiya et al. 2005).

Importantly, some flavonoids protect plants from heavy metal stress as they are proficient metal (such as Cu, Zn, Fe) chelators, avoiding creation of hydroxyl radicals through Fenton's reaction (Williams et al. 2004). Flavonoids can protect plants from the toxicity of high heavy metal concentrations in soils by chelating these metals (Kidd et al. 2001). Flavonol group molecules have three main sites that can be potentially coordinated with transition metal ions including the 3-hydroxyl and the 4-carbonyl groups in the C ring, the 5-hydroxyl group of the A ring and the 4-carbonyl group in the C ring and the 3′- and 4′-hydroxyl groups of the B ring (Fig. 6) (Rice-Evans 2004; Williams et al. 2004; Samsonowicz and Regulska 2017). Pietta (2000) suggested that the binding sites for metals in the flavonoid molecules are the 4-oxo and 5-hydroxyl groups between the A and C rings and the catechol moiety in the ring B, the 3-hydroxyl and 4-oxo groups in the heterocyclic ring C (Fig. 6). The importance of the catechol moiety in the B ring for the Cu^{2+} chelate formation has been reported by Brown et al. (1998) as the major contributory site of the copper chelation (Brown et al. 1998). Quercetin is a well-recognized compound for chelate formation and stabilization of iron ions. Due to considerably high antioxidant activity and complex formation with Cd(II) and low toxicity, sulfonic water soluble derivatives of quercetin and morin are reported as potential candidates for detoxification of cadmium (Chlebda et al. 2010).

Kostyuk et al. (2004) demonstrated that metal-flavonoid chelates display superoxide dismutase activity. For example, Bota et al. (2011) demonstrated a correlation between flavonoid and $CuSO_4$ concentrations in cell cultures of *Digitalis lanata*. Similarly, this was confirmed by Kidd et al. (2001) in corn plants (*Zea mays* L.) grown on soil contaminated with aluminum ions, where high levels of catechin and quercetin in the root exudates were observed.

Flavonoids are also important molecules in metal chelation and reduction and in nanoparticles formation (Makarov et al. 2014). This ability is due to the presence of functional groups including carbonyl moiety and multiple hydroxyl groups (Marslin et al. 2018). Moreover, the possible role in metallic ions' reduction through the transformation of internal ketones into carboxylic acids in these compounds has been discussed (El-Seedi et al. 2019). Finally, it should be noted that chelate formation of metal ions by some flavonoids can happen by the carbonyl group or π-electrons of these molecules; as an instance, extracted apiin (apigenin glycoside) from *Lawsonia inermis* was successfully applied for the synthesis of anisotropical Au nanoparticles and quasispheroidal Ag nanoparticles (Kasthuri et al. 2009).

Tannins

Tannins are a class of phenol-containing macromolecules that are synthesized by higher plants and accumulated in their tissues (e.g., making up about 30% of the dry mass of tea) (Shirmohammadli et al. 2018). They are categorized as water soluble phenolics compounds with a molar mass in the range of 300 and 3000 Da with some common features that enables the classification of these types of compounds in two main groups: hydrolysable tannins and condensed tannins (Khanbabaee and van Ree 2001). Hydrolysable tannins include gallotannines and ellagitannines that are respectively comprised of gallic acid or hexahydroxydiphenic acid esters linked to a sugar moiety, while more complicated ones can be formed by oxidative transformations that can yield macrocyclic ellagitannins (Okuda et al. 2000). However, the chemical structure of gallotannines depends on the plant species producing the compound and until now more than 8000 different tannins have been isolated and characterized and certainly, there are many more tannins that their chemical structure and characteristics have not been precisely determined yet. Condensed tannins

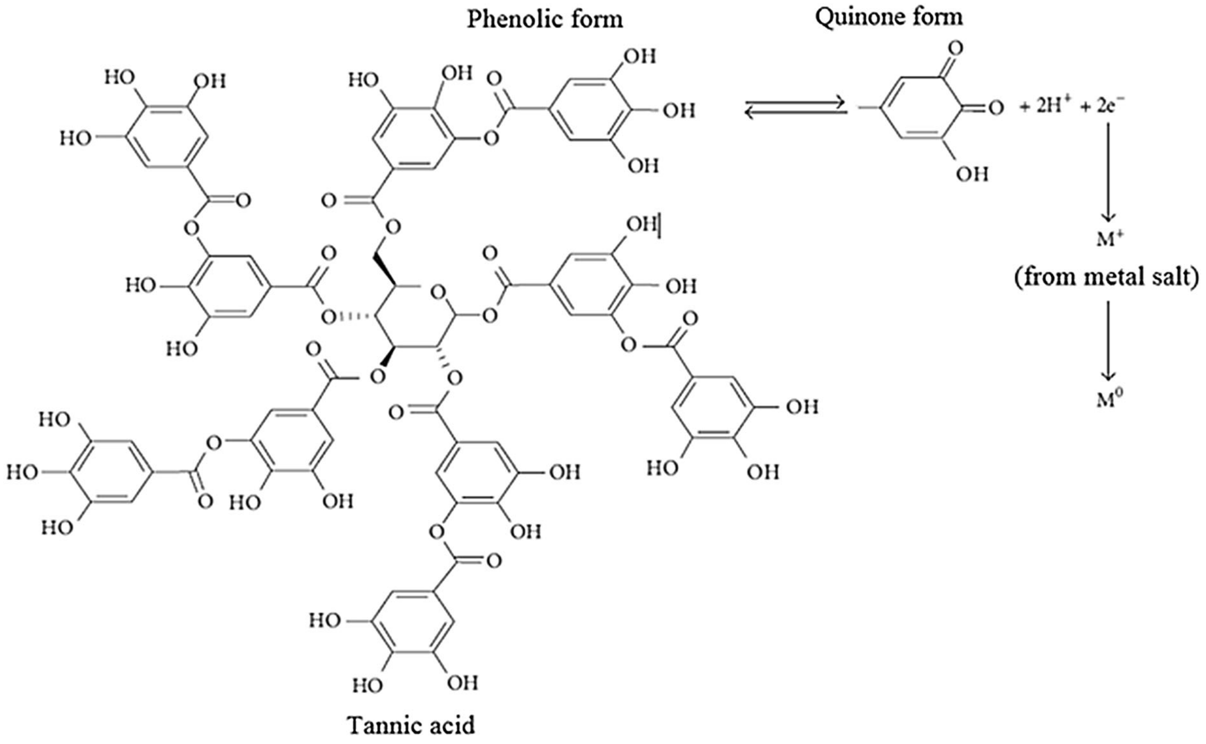

Fig. 7 Metal ion reduction mechanism by tannic acid-based compounds (Ahmad 2014)

(nonhydrolyzable), also called procyanidins, are polymers containing three ring flavanols linked with carbon-carbon bonds. Monomer units of condensed tannins are identified by the number of hydroxyl groups on the B-ring: procyanidins have a di-hydroxy B-ring, but prodelphinidins have a tri-hydroxy B-ring (Kraus et al. 2003). These monomer units might have a stereochemistry of both *cis* and *trans* C2–C3 (Schofield et al. 2001).

Tannins are cheap and widespread natural polyphenolis and are well known for their biological activities including their potential to serve as antioxidants, protein precipitants and metal chelators. Following cellulose, hemicellulose and lignin, they have the highest abundancy in plant biomass (Arbenz and Avérous 2015). The tissues of plant species from the families of *Theaceae*, *Vitaceae*, *Myrtaceae*, *Punicaceae*, *Actinidiaceae*, *Juglandaceae*, *Fagaceae*, *Rosaceae etc.* are rich in tannins (de Jesus et al. 2012; Smeriglio et al. 2017). Studies suggest that high tannin content can help plants to overcome the toxicity of high levels of metals in soils (Michalak 2006). Frequent catechol and galloyl groups, allow tannins to form stable chelates with some transitional metallic ions like iron among other metals (Lee et al. 2017). Yokozawa et al. (1998) reported that in tannins, the higher molecular weight and quantity of galloyl groups, as well as the existence of ortho-dihydroxy structure, significantly enhances their scavenging activity. Ellagitannins and gallotannins molecules possess many different chelating groups, which enable them to chelate efficiently ferric iron in solution and form blue-black precipitates, or to separate and extract it from alternative iron/ligand complexes rather than other low molecular weight and monofunctional phenolic compounds (Mila et al. 1996). Proanthocyanidins are capable Fe(III) chelators (Santos-Buelga and Scalbert 2000). Epigallocatechin gallate, the lowest molecular weight tannin, forms strong complexes with ferric ion at a stoichiometric ratio of 2:1 at pH 7 (Karamać and Pegg 2009).

A study by Oladoja et al., (2011) shows that tannin resins interact with metals through complex formation and ion exchange. They discussed that metal complexation occurs by two adjacent hydroxyl groups (catechols), while a third adjacent hydroxyl group (pyrogallols), enhances the stabilization of the formed complexes. Additionally, dissociation of the surface groups by the increase of the pH, increases the metal complexation potential and electrostatic attraction by tannins (between the surface of the negative biosorbent and the positive adsorbate). These are the reasons why the patterns observed in terms of pH influence assays carried out for Cu(II), Pb(II), Zn(II) and Ni(II), which shows an increase of the adsorbed amounts with the raise of pH, in acidic range, with highest removals reached at pH 4 or 5 (Şengil and Özacar 2008; Yurtsever and Şengil 2009).

Tannin gels have a high tendency to interact with heavy metals including lead (Yurtsever and Şengil 2009; Şengil and Özacar 2009), chromium (Nakano et al. 2001; Inoue et al. 2010; Alvares Rodrigues et al. 2015), copper (Şengil and Özacar 2008, 2009), and zinc (Şengil and Özacar 2009; Arasaretnam and Karunanayake 2010) in aqueous solutions. In addition, different works with wattle tannins, obtained from the bark of black wattle (*Acacia mearnsii*) trees that are commercially available, revealed precious metal complex formation with metals such as Pd(II) (Kim et al. 2007), Pt(IV) (Morisada et al. 2011), Au(III) (Ogata and Nakano 2005) and Ag(I) (Cataldo and Angelini 2013).

In tannic acids, through the oxidization of phenolic groups to quinones, electrons are released which may consequently get involved in the reduction of metallic ions (Fig. 7). Phenolic and polyphenolic compounds are electron rich and strong antioxidants, which comprise their ability to release free reactive hydrogen atoms (Aromal and Philip 2012).

Different industrial applications of tannins or tannin-based compounds rely on the complex formation with metal ions. Humans have taken advantage of the coordination complex of Fe(III) ions with tannins (Lee et al. 2015; Park et al. 2017) throughout history, such as iron gall ink, which has been used since the Middle Ages in Europe (Han et al. 2019). Other applications of tannins in industry include their use as: corrosion inhibitors for steel (Rahim et al. 2011; Rahim and Kassim, 2008) and non-ferrous metals (Kusmierek and Chrzescijanska 2015), modifiers of rheological properties of minerals and clays (Chang and Anderson 1968) for applications in mineral flotation, ceramic, cement and drilling industries, agents for heavy and precious metal recovery from wastewaters (Nakano et al. 2001).

Only strong oxidants are able to oxidize tannins. However, the formed phenoxyl radical is able to interact with metals (Jovanovic et al. 1998). The

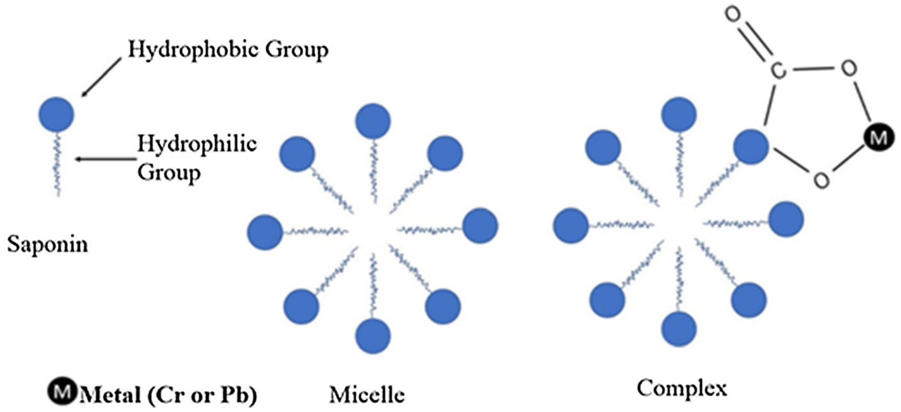

Fig. 8 Reaction mechanisms of metal ions with hydroxyl and carbonyl groups of saponins (Tang et al. 2017)

existence of several phenolic groups in the structure of tannic acids, which participate in the redox reactions through electron donation and quinone formation, makes these strong reducing properties (Ahmad 2014).

Saponins

Saponins are natural glycosides of steroids, or triterpenoids (sapogenins) and a carbohydrate moiety by ester or ether linkages with foaming characteristics. They are a class of non-ionic biosurfactants found in more than 500 kinds of plants with high surface activity, biodegradability, eco-friendly and low toxicity (Tang et al. 2017). They are included in a large group of protective molecules named '*phytoprotectants'* or '*phytoanticipins'* (Francis et al. 2002) and can make up to 30% of the plants' dry mass (Fenwick et al. 1991). Saponins are divided in eleven main classes including dammaranes, cycloartanes, tirucallanes, oleananes, lupanes, taraxasteranes, ursanes, lanostanes, hopanes, cucurbitanes and steroids.

Saponins are present in different plants mainly in legumes and some medicinal herbs. Alfalfa (*Medicago sativa*), sarsaparilla (*Smilax regelii*), licorice (*Glycyrrhiza* species like *Glycyrrhiza glabra*), soapwort (*Saponaria officinalis)*, soap bark tree (*Quillaja saponaria*), *Gypsophila* genus (like *Gypsophila paniculata*), horse chestnut (*Aesculus hippocastanum*), fenugreek *(Trigonella foenum-graceum)* and Mojave yucca (*Yucca schidigera*) are the most important non-food saponins sources that are being used in different applications (Hostettmann and Marston 1995; Balandrin 1996). Because of the existence of a lipophilic aglycone (sapogenin) and hydrophilic sugar chain, saponins have amphiphilic properties resulting in foam formation (with liquid-gas phases), dispersion abilities (with liquid-solid phases) and emulsifier effect (with liquid-liquid phases) (Kregiel et al. 2017), and thus have been used as a detergent (Vincken et al. 2007).

Saponins are also reported as important agents for the heavy metal removal from aqueous wastes aiming for the remediation of contaminated sites due to their ability to form chemical complexes with metals (Abed el Aziz et al. 2017). In fact, different studies describe saponins as naturally occurring chelating agents that can be used for the elimination of contaminants caused by several heavy metals including Cd, Pb, As, Cr, Cu and Zn from contaminated waters and soils (Kiliç et al. 2011). It is reported that saponins can remove and retain heavy metals from their original solutions by complex formation with their carboxyl group (Gao et al. 2012a). Saponins are very suitable compounds for remediation of very low concentrations of heavy metals due to the presence of hydroxyl and carbonyl groups in their structure (Fig. 8) (Chen et al. 2008). During the heavy metal (like Pb, Cr, Cu, Ni, Zn) removal through different procedures such as sequential sludge washing, Huang and Liu (2013) described saponins' capability in complex formation with the mentioned heavy metals. Moreover, Zhou et al. (2011), applied saponins to extract heavy metals and hydrophobic organic compounds (HOCs). From a chemical point of view according to El-Aziza (2018), heavy metal-saponin biochemical reactions can be considered as a contemporary process in decontamination of industrial and other metal contaminated effluents and the synthesis of new organometallic complexes. Furthermore, there are studies suggesting that saponins can extract heavy metals from contaminated soils even more effectively than with conventional surfactants (Gusiatin and Klimiuk 2012; Maity et al. 2013). Metal removal from soil and aqueous solutions by saponins must be due to strong bond formation between the metal ions and saponin as a complex (Munichandran et al. 2016). The most important chemical factors that may affect the reactions between metal bearing solutions and saponins are metal concentration, pH of the solution and the amount of saponin.

Saponins are usually extracted by liquid-liquid extraction or column chromatography. Also, saponins can be extracted by DES (Zainal-Abidin et al. 2017). During the storage or processing, specially by acid/base treatments or microbial/enzymatic transformations, the main structure of saponins can change due to the hydrolyzation of links between sugar chains and aglycones, or between sugar residues, resulting in the formation of aglycones (sapogenins), sugar residues and partially hydrolyzed saponins (prosapogenins) (Oleszek and Hamed 2010). Accordingly, plant substances must be stored using suitable techniques based on the target compound as in every efficient technology.

Polysaccharides

It is well known that polysaccharides are chain carbohydrate molecules originating from plants and therefore are abundant, renewable and biodegradable resources with the capacity to be interacted by chemical and physical mechanisms to an extensive number of molecules (Ciesielski et al. 2003). During the last few decades many studies were focused on the synthesis of cost-efficient biosorbents from the biomass of different resources (Won et al. 2014). Between different materials, plant polysaccharides (like cellulose) were found to be very suitable candidates for the adsorption of various metal ions (Gurung et al. 2014).

In their polymeric chain, polysaccharides possess several functional groups (carboxyl, hydroxyl and amino), which gives them their high and selective metal adsorption capacities (O'Connell et al. 2008; Liu et al. 2013). Hence, due to their metal binding capacity and high availability, polysaccharides and their derivatives-based adsorbents could be considered as an economically viable approach in metal extraction and remediation of water sources. Because of the protonation and deprotonation of polysaccharides' functional groups (especially amine groups in amino sugars), their adsorption behavior for metal ions is influenced by the pH and because of this, they can be positively or negatively charged with varying metal sorption mechanisms. Biosorption is a combination of different mechanisms including complexation, ion exchange, electrostatic attraction, adsorption, Van der Waals attraction and covalent binding (Montazer-Rahmati et al. 2011; Witek-Krowiak 2012).

Polysaccharides such as starch (Yuryev et al. 2002) and their derivatives (cyclodextrin) (Del Valle 2004) are effective natural metal adsorbent polymers. However, natural forms of polysaccharides have inadequate chemical resistance and structural strength, making them unsuitable for a direct application as biosorbents. Therefore, these natural compounds need some chemical modifications by cross-linking and surface grafting to be more efficient biopolymeric adsorbents. For example, there are works suggesting

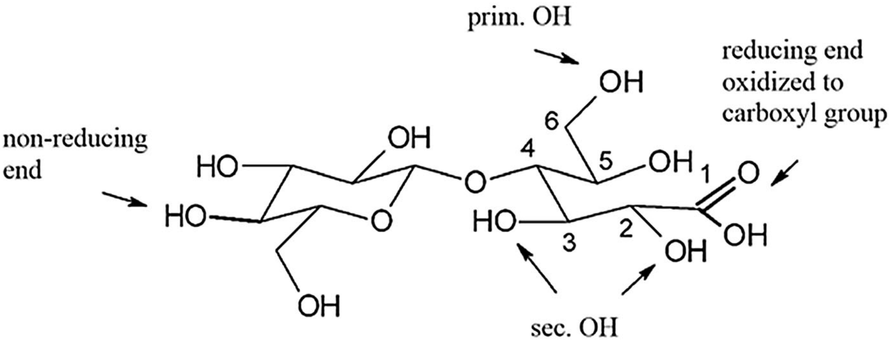

Fig. 9 Functional groups present in processed cellulose (Wurm et al. 2020)

that the modifications could be applied to starch in order to make it a good adsorbent for heavy metals and dyes by the introduction of active groups like carboxylate, xanthate, amine phosphate, acrylate and many other groups that have chelating abilities (Kweon et al. 2001). Crini (2005) showed that several hundred ppm of divalent metal ions (Cu, Pb, Cd and Hg) could be extensively removed from water by dispersing 1% of the modified starch in a few minutes. It is suggested by Kim and Lim (1999) that starch, after the crosslinking with carboxymethylation and $POCl_3$, could be a good sorbent for the different heavy metal ions.

Many of the cellulosic-based sorbents have high metal ion interaction potentials and a part of them present better selectivity towards some precious metals in highly acidic conditions (Pangeni et al. 2012; Dwivedi et al. 2014). In a related work, in order to improve biosorption performance, cellulosic based sorbents underwent some modifications with sulfonic, sulfhydryl or amino groups (Dwivedi et al. 2014). Many different studies used powdered plant containing cellulose or alginate and they were successfully used as biosorbents (Vijayaraghavan et al. 2011; Jain et al. 2016; Wang et al. 2021). Precious metal recovery by polysaccharide-based biosorbents has been the main focus of many studies for a long time. Amongst different types of polysaccharides, cellulose and alginate could be efficient base matrices for the recovery of heavy and precious metals (O'Connell et al. 2008; Abdolali et al. 2014).

The main mechanisms known for metal and dye adsorption on cellulosic biosorbents is chelation and ion exchange, which frequently results in H_3O^+ being released into the aqueous solution (Abdolali et al. 2014). As depicted in Fig. 9, a free hydroxyl group is present at one end of the cellulose chain and is referred as the non-reducing end, whilst an aldehyde group at the other end of the chain is called a reducing end, which can simply get oxidized to carboxylic groups (Wurm et al. 2020). Ionic exchange is a process including electrostatistical interchanges among cations and negatively charged groups of plants' cell walls (Fiol et al. 2006).

Applications of the plant-based compounds with metal interaction ability

Strict environmental regulations applied to contaminants discharged from industrial operations are being introduced in most of the developed and developing countries (Abdel-Aty et al. 2013). Commonly used methods of metal recovery/removal from solutions and soils are ion exchange/chelation, precipitation, solvent extraction/liquid membrane and electrolytic recovery (Li et al. 2009; Hong-Bo et al. 2010). These procedures are frequently not economically viable and there is a lack of efficiency in metal recovery or removal especially when the concentration of metals in wastewaters is low (Hammaini et al. 2003). Beside this, the chemical compounds being used in the metal industries and then released into the environment in wastewaters could be harmful to both ecosystems and human. Thus, in recent years, more attention has been paid to biological methods for the treatment of heavy metal bearing effluents aiming to reduce their concentrations in the environment to acceptable levels. For this reason, utilization of plant-based compounds can represent a promising alternative that deserve to be explored.

Some of the most important biological methods based on active compounds obtained from plant materials have been previously tested in research studies and thereafter introduced for industrial purposes. Additional applications of plant-based compounds benefiting from their metal interaction capacity are also reviewed. These methods are supposed to be more cost effective, attractive from an environmental point of view and efficient in terms of metal interaction efficiency.

Metal insolubilization

Chemical precipitation of metals is one of the most widely used methodologies applied for metal/heavy metal removal from different metal contaminated effluents. However, conventional methods like chemical precipitation that are being used for the treatment of wastewaters polluted with metals have some limitations. These methods present weak aspects such as slow metal precipitation and partial metal removal (Aziz et al. 2008), the creation of huge amounts of metal polluted sludge (Ayangbenro and Babalola 2017), high costs, energy and reagent requirements

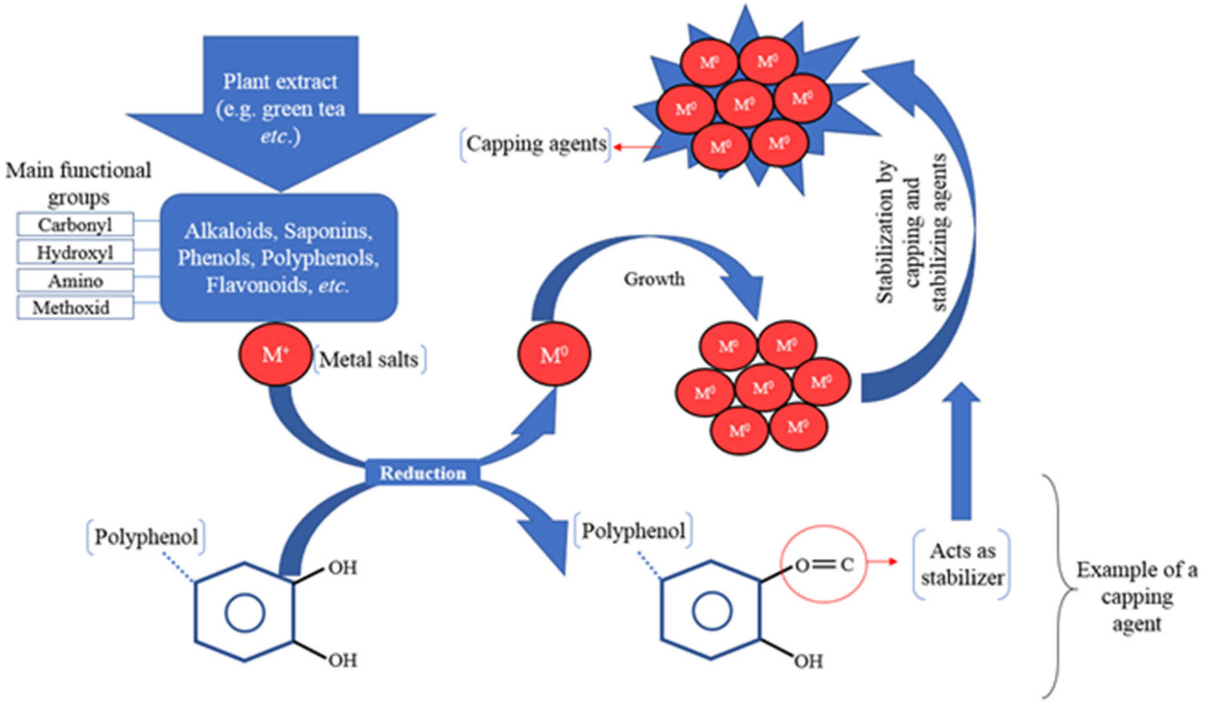

Fig. 10 Suggested mechanism for metal reduction and metallic nanoparticle synthesis

and problems related to precipitates solubility and the clogging (Kanamarlapudi et al. 2018).

Plant compounds such as phenols, saponins, alkaloids etc. extracted from plants have potential to precipitate metals depending on their nature and this ability usually relies on complex/chelate formation and the reduction of metals by these compounds. As an example, these compounds could be utilized to precipitate or separate different metals from metal bearing solutions. For instance, McDonald et al. (1996) reports the successful precipitation of zinc and copper using tannins and low molecular weight phenols extracted from plants. Gatew and Mersha (2015) used *Moringa stenopetala* seed powder extract to remove chromium from tannery wastewater which results in 99.86% of chromium removal. In addition, Agwaramgbo et al. (2012) described the successful lead (Pb) precipitation from an aqueous solution by aqueous extracts of some plants. In another work, (Lathan et al. 2013) Lathan et al. (2013) used some plant extracts rich in polyphenols to remove lead from a solution (with initial concentration of 1280 mg/l) and reported that spinach, tea and instant coffee extracts efficiently precipitated more than 90% of the lead in the solution. These results proved the metal bio-reduction methods assisted by plant extracts rich in phenols/polyphenols is very effective to remove and recover metals from wastewater.

Moreover, some researchers suggested that saponins could be applied as natural chelating agents to solve the problems caused by different heavy metals like Cd, Cr, Zn, Cu, As and Pb from wastewater and soil (Kiliç et al. 2011; Gonzalez-Valdez et al. 2013). The presence of strong bonds in saponin-metal complexes is considered to be the reason for metal removal from soils and solutions (Munichandran et al. 2016). Abed El-Aziz et al. (2017) have successfully prepared heavy metal saponin complexes by combining water extract of *Citrus aurantium* and *Olea europaea* and heavy metal bearing solutions.

Metal precipitation by plant extracts depends on some operational factors like settling time, type of plant compound in plant extract, metal/heavy metal type and concentrations, extract concentrations, pH and temperature which can affect the metal precipitation process.

Synthesis of metal nanoparticles

Nanoparticles are a special group of materials with a dimension below 100 nanometers that due to their small size have unique features and extensive applications in miscellaneous fields (Mohamad et al. 2013). Metallic nanoparticles are nowadays widely used compounds with many applications such as degradation of dyes (Vomáčka et al. 2016), catalysis (Yang et al. 2010), antibacterials (Naika et al. 2015) and gas sensors (Su et al. 2015). Nanoparticles are usually synthesized through physical and chemical procedures, that are mostly expensive and non-environmentally friendly (Makarov et al. 2014).

In parallel with growing consciousness of the necessity of green chemistry and sustainability, environmentally friendly methods for biosynthesis of nanoparticles are gaining more attention. One of the methods to synthesize nanoparticles is the green synthesis technique which is ecological friendly, simple, cheap and very fast (Mittal et al. 2013). Biosynthesis of nanoparticles by plant extracts is a way to reduce the use of hazardous chemicals compounds, avoiding the environmental pollution and therefore the biological routes for synthesis of nanomaterials are getting more popular. Nanoparticles synthesized using plants are reported to be highly stable and more variable in shape and dimensions (Iravani 2011). It is shown by many research studies that plants containing high amounts of active metabolites including phenols, flavonoids, saponins, steroids, alkaloids that can act as reducing, capping or stabilizing agents, have substantial capabilities to reduce and maintain metals into their respective nanoparticles (Ajitha et al. 2016; Mystrioti et al. 2016; Sigamoney et al. 2016; Martínez-Cabanas et al. 2016; Devatha et al. 2016; Siddiqi and Husen 2017). Utilizing plant extracts as reducing, capping and stabilizing agents obviates the need to use different chemical reagents for all those purposes (El-Seedi et al. 2019).

Capping agents are biological or chemical components (Fig. 10) that naturally restrict the reaction and the particle growth in the nanoparticles synthesis; the reduced metals form nanostructures like nanoparticles or nanocrystals, which needs to be capped appropriately to be stable, biocompatible and functional against aggregation in different biological systems (Vadlapudi 2015). Capping agents follow different mechanisms such as steric and depletion stabilization, electrostatic, hydration and van der Waals forces (Kim et al. 2004). Usually, the H-donating ability of polyphenols are associated to the metal ion reduction capacity. Due to the redox reaction that leads to the reduction of metal ions, the OH group in the reduced form of polyphenols is converted into a carbonyl group (C=O), that electrostatically stabilizes the metal nanoparticles (Fig. 10) (El-Seedi et al. 2019).

Biosynthesis methods for metallic nanoparticle production are obviously more cost-efficient and environmentally friendly than other physical or chemical procedures. Even though the biosynthesis of metallic nanoparticles by plant compounds has been extensively studied, the exact mechanisms of the process are not clearly understood (Punjabi et al. 2015). However, the main functional groups present in different plant compounds such as carbonyl, hydroxyl, methoxide and amino are known to bind to metal ions through electrostatic interactions and reduce them (Küünal et al. 2018). Hydroxyl groups and other substituents, such as methoxyl or carboxyl groups in the phenolic compounds are key groups for the metal chelation potential of those plant-based compounds.

There are many reports regarding different metallic nanoparticle synthesis using plant compounds; for instance, *Ambrosia maritima, Callicarpa maingayi* and *Coleus aromaticus* extracts were used for the synthesis of metallic Ag nanoparticles (Shameli et al. 2012; Vanaja and Annadurai 2013; El-Seedi et al. 2016). Polyphenols extracted from the leaf of *Tabebuia berteroi* (Vellaichamy and Periakaruppan 2016) and flavonoids, tannins and phenolics extracted from *Withania coagulans* are shown as responsible compounds for the reduction of lead and iron ions into their metallic nanoparticles, so along with graphene oxide (rGO) the respective nanocomposite is formed (Atarod et al. 2016). The flower extract of *Anthemis xylopoda* (Nasrollahzadeh and Sajadi 2015a, b), leaf extract of *Ziziphus ziziphus* (Aljabali et al. 2018), extract of *Garcinia mangostana* fruit peels (Xin Lee et al. 2016) and many others were reported for Au(III) reduction into Au(0) nanoparticles. Also, Nasrollahzadeh and Sajadi (2015a, b) used the quercetin (flavonol) rich leaf extract of *Ginkgo biloba* to reduce Cu(II) to Cu(0) nanoparticles in a two-step process, without requiring any additional agents for capping or stabilizing the particles.

Some other examples of metal oxide nanoparticle synthesis using plant extracts include CdO using

Parkia specioasa (Permana and Yulizar 2017), Fe_3O_4 using *Graptophylum pictum* (Sari and Yulizar 2017) and ZnO using *Imperata cylindrica* (Saputra and Yulizar 2017). It is reported that *Euphorbia peplus* extract containing high levels of flavonoids and rare disaccharides, reduces $AgNO_3$ in the presence of Fe_3O_4 and stabilize the formed silver nanoparticles with enhanced catalytic activity (Sajjadi et al. 2017). In another work, Pd/CuO nanoparticles were effectively synthesized by seed extracts of *Theobroma cocoa*, which contains phenolic antioxidants (Nasrollahzadeh et al. 2015). There are also other reports about the synthesis of CuO nanoparticles, using extracts of *Thymus vulgaris* (Nasrollahzadeh et al. 2016), *Gloriosa superba* (Naika et al. 2015), *Citrus lemon* (Mohan et al. 2015), *Euphorbia tirucalli* (Ravikumar et al. 2014), *Tamarindus indica* (Ankamwar et al. 2005), *Azadirachta indica* (Shankar et al. 2004) and *Cinnamomum champora* (Huang et al. 2007). Nasrollahzadeh et al. (2015) synthesized very stable TiO_2 nanoparticles using *Euphorbia heteradena* extract, reporting phenolic compounds present in the extract as key factors for the reduction of the metallic ions and capping the ligands on the nanoparticle surfaces, as evidenced via FTIR (Fourier-Transform Infrared) spectroscopy. FTIR studies reported the frequent association of terpenoids with biosynthetic metallic nanoparticles (Kavitha et al. 2017).

Other studies also suggest that proteins are effective compounds in the biosynthesis and stabilization of metallic nanoparticles (Balaji et al. 2009). Durán et al. (2015), throughout the biosynthesis of nanoparticles reports a great number of molecules, comprising amino acids and proteins with exposed disulfide bridges and thiol groups, acted as non-enzymatic capping and reducing agents. Moreover, Jain et al. (2011) identified two extracellular proteins and illustrated their roles in the biosynthesis and stabilization of silver nanoparticles.

The type and concentration of compounds present in plant extracts have high impact on the morphology of the synthesized nanoparticles, whilst the size of the particles is mainly affected by the pH and temperature of the medium (Sankar et al. 2014). Moreover, the concentration of metal ions controls the shape and size of the formed nanoparticles (Huang et al. 2007; Makarov et al. 2014). Furthermore, to synthesize nanoparticles with a controlled size and morphology, proteins and peptides can be added as biomatrices (Makarov et al. 2014). The biosynthesis of the nanoparticles allows the size and shape of the particles to be controlled due to the extremely specific reactions

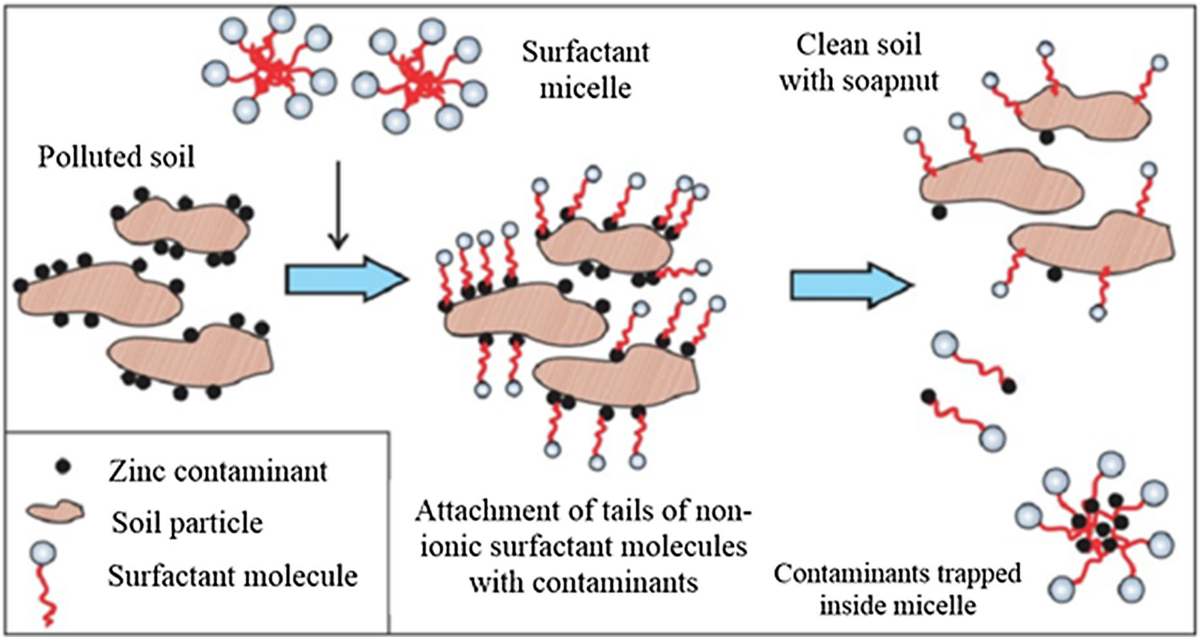

Fig. 11 Biodegradable plant-based surfactant (saponin) (Mukhopadhyay et al. 2018)

among the biomolecular templates and inorganic compounds (Das et al. 2012).

Biosorption

Biosorption is explained as the ability of a biomass to bind and concentrate metals from an aqueous solution to its structure. It is the most widely studied mechanism of metal removal that in comparison with other metal recovery/removal procedures, has high-rate kinetics, high capacity and metal selectivity balanced by the synthesis method, which makes the mechanism suitable for the complex metal polluted water streams in high volumes and low concentrations (Wang and Chen, 2009). Ideal biosorbents need to be abundant and easily accessible, stable in different conditions, have great potential for the target metals, highly selective and present simple separation from the solutions (Wang and Chen, 2014). However, one of the most important disadvantages of biosorption is that the reutilization of the sorbent material is frequently difficult, usually due to low recovery of the metal from the sorbent material. Metals biosorption on the surface of biosorbent may occur through several mechanisms including complexation or chelation, ion exchange, reduction, electrostatic interactions and microprecipitation. Different active functional groups presented on biosorbents like carboxyl, hydroxyl, amine and phosphoryl are determining for these interactions (Won et al. 2014).

A wide variety of agricultural by-products and fruit wastes such as sugarcane bagasse, banana cortex, soya bean hulls, lemon and orange peel, walnut hulls, cotton seed hulls, corn cobs and carrot residues (Kelly-Vargas et al. 2012) were used for metals biosorption. Phenolic and carboxylic functional groups present either in the cellulosic matrix or in materials related to cellulose, such as hemicellulose or lignin, can be the reason of the cation exchange properties in these residues (Nasernejad et al. 2005).

Even though the emphasis of this review is the plant-based compounds, it is worth mentioning the potential of different algal species as biosorbents and their application to the treatment of metal polluted wastewaters and/or metal recovery, because of their high sorption potential and availability.

Bioremediation of heavy metals in soils

Washing the soils using natural surfactants is a suitable alternative for the heavy metal contaminated soil remediation (Fosmire 1990). Mainly, there are two technologies to remediate the metal contaminated soils (Dermont et al. 2008). One is to immobilize heavy metals through tightly bounding the metals to soil compounds in order to minimize migration. The other consists of metal mobility by moving them to a solution by solubilization and elution in a washing solution (Pathak et al. 2009; Zhang et al. 2010a). The second process usually employs wash solutions that contain chelating agents (Zhang et al. 2010b; Zou et al. 2009), acids (Wen et al. 2009), or other suitable compounds such as surfactants (e.g. saponins) (Arwidsson et al. 2010; Guo et al. 2010) as shown in Fig. 11.

Different studies regarding the application of saponins from sources other than soapnut show heavy metal (e.g. Zn, Ni, Cd and Cu) removal from soil and a removal up to 90%, depending on the soil type and contaminant level (Song et al. 2008; Gusiatin and Klimiuk 2012). Desoky et al. (2019) supplemented saline soils contaminated with heavy metals with root extract of *Glycyrrhiza glabra* through irrigation water and analyzed its effect on the growth of *Capsicum annuum*. Their results revealed a significant reduction in the content of the contaminant metals', such as Cd, Pb Ni, Cu, and Na in the plants. They hypothesized that some proteins with low molecular mass such as metallochaperones or chelators like nicotianamine, phytochelatins, spermine, mugineic acids, putrescine, metallothioneins and organic acids, or extracellular compounds including phenolics and flavonoids, heat shocked proteins, protons and some particular amino acids like proline and histidine, are possible plant compounds present in the extracts that immobilized/washed metals and reduced the negative effect of these contaminants.

Corrosion inhibitors

Metal corrosive inhibitors are usually organic compounds with an abundant number of oxygen, nitrogen and sulfur atoms with aromatic compounds (Moura et al. 2013; Felipe et al. 2013); the lone pair of electrons present on these atoms is transferred to the metal surface thus, avoiding the loss of electrons by the metal, since their molecules form bonds on the metal surface, blocking the active corrosion site. Frequently, many of these compounds are highly hazardous for the environment and organisms and therefore, substitution of naturally produced compounds as environmentally-safe and non-toxic corrosion inhibitors has become popular (Raja and Sethuraman 2008; Prabha et al. 2012). Plant based corrosion inhibitors can be used as an effective substitute for the currently exploited organic inhibitors, due to the presence of significantly better inhibitive properties than the currently employed organic inhibitors (Baban and Milind 2011).

Recently, green corrosion inhibitors are becoming more popular because of the increase in environmental awareness that has led to restrictions and regulations of toxic corrosion inhibitors. Consequently, many studies regarding alternative and less toxic inhibitors have been reported (Li et al. 2008). Green corrosion inhibitors form a layer on the metal surface through adsorption and create a protective layer (Hefter et al. 1997). That protective barrier interacts with anodic or cathodic reaction sites and decreases the corrosive reactions (Singh et al. 2016). Green corrosion inhibitors have adsorptive characteristics that are recognized as site blocking substances (Sanatkumar et al. 2012). Studies suggest that plant extracts of *Piper nigrum* rich in phenolics, alkaloids, terpenoids or other biomolecules (such as proteins, carbohydrates and lipids) can act as corrosion inhibitors (Raja and Sethuraman 2008). There are many recent studies regarding the efficiency of different plant extracts like *Ficus tikoua* (Wang et al. 2019), olive leaves (Ben Harb et al. 2020) and *Celtis tournefortii* fruit (Sedik et al. 2020) as steel corrosion inhibitors, *Idesia polycarpa* fruit extracts as copper corrosion inhibitor (Zhang et al. 2020), *Bagassa guianensis* as zinc corrosion inhibitor (Lebrini et al. 2020) and *Sapium ellipticum* as aluminum corrosion inhibitor (Okechukwu Dominic et al. 2020).

Kundu et al. (2016) reviewed the effects of the green corrosion inhibitors in rebar embedded on concrete in pH conditions between 12 and 13. In this review, they explained the effect of *Bambusa arundinacea* extract as being due to its strong hydrophobic effects, which helps the development of a two-faced layer of iron oxides (Fe_3O_4 and Fe_2O_3) adsorbed to the steel surface (Asipita et al. 2014), or as spinel α-Fe_3O_4–γ-Fe_2O_3 solid solution that forms an inactive layer on the steel (Abdulrahman and Ismail 2011). Rosaline Vimala et al. (2012) explained that the inhibition efficiency of *Annona muricata* L. acid extract may be due to the adsorption of an alkaloidal compound named 6-hydroxyundulatine and other alkaloids on the metal surface, thereby blocking the surface and protecting the metal from the aggressive atmosphere.

Pharmaceutical applications

It is well known that heavy metals (e.g., Cr, Cd, Pb and Hg) and also the accumulation of essential heavy metals (Zn, Cu, Fe, and Co) may cause different disorders in the human body. Metal ions can have some interactions with different cellular units like DNA or nuclear proteins causing apoptosis, harmful carcinogenic structural changes (Mehrandish et al. 2019), initiation of reactive oxygen and nitrogen species resulting from the peroxidation of lipids in the plasma membrane (Kim et al. 2019) and also, catalysis the generation of hydroxyl radicals via Fenton like reactions (Valko et al. 2016). The use of compounds able to chelate metals are in the origin of several treatments regarding the above-mentioned diseases and the search for natural and less toxic chelating agents for such purpose is a topic greatly investigated.

Antioxidants

Nowadays, antioxidants with a significant potential role in pharmaceutical and agri-food industries are getting increasingly popular. They are known as compounds with potential to interact with oxidizing agents, inhibiting their consequent damage to other molecules or cellular components as well as substances with abilities to repair a system such as iron transporting proteins (Brewer 2011).

Flavonoids have antioxidant properties due to their potential to chelate iron which can damage protein and lipid on cell membrane and regulate many signaling pathways such as the inhibition of xanthine oxidase which is considered as a source of reactive oxygen species that causes the oxidative stress (Cos et al. 1998). Tannins are well known to have the ability to interfere with cell-based activity assays and also to display antioxidative effects (Zhang et al. 2010a, b).

Various studies have shown that green tea and epigallocatechin gallate significantly avoid misregulation of iron metabolism, preventing the neurodegenerative diseases in animal models (Levites et al. 2001). In addition to their well-established metal-chelating properties, polyphenolic compounds like catechins are known as radical scavengers of oxygen and nitrogen species and therefore, regulate the cellular redox state (Higdon and Frei 2003). Their chelating potential may interfere with iron and neutralize the ferric iron to form redox inactive iron, providing a protection for cells against oxidative damages (Grinberg et al. 1997). Natural antioxidants like phenolics present in dietary resources such as resveratrol in peanuts and grapes, catechins, and theaflavins in tea, curcumin in turmeric and anthocyanins in berries are able to form adducts with metals and thus reverse ROS generation (Uttara et al. 2009; Ratheesh et al. 2017).

Ascorbic acid serves as an antioxidant that is essential for the preventing and treatment of scurvy. It has been shown that vitamin C reduces transitional metals, as an instance, Cu^{2+} into Cu^{+} and Fe^{3+} into the Fe^{2+} (Satoh and Sakagami 1997).

Chelation therapy

Interest in utilization of plant extracts and plant-derived compounds for metal chelation is increasing and a new field recognized as ‘natural chelation therapy’ in medical sciences is arisen. Chelation therapy is defined as a treatment method for the reduction of unnaturally accumulated essential heavy metals (like Cu, Fe and Zn), or other inessential toxic metals (like Al, Cd and Pb) (Andersen 2004). In fact, chelating agents form complexes with metallic ions and enhance their discharge through urination and fecal excretion and finally a reduction of their body concentrations (Hegde et al. 2009). Some natural polymers with the potential of heavy metal absorption such as chlorella and citrus pectin, algal polysaccharides alginate and also fibers in foods, like cereals and fruits are also potent compounds for chelation therapy besides the main treatment processes (Mehrandish et al. 2019).

It has been shown that modified citrus pectin, a linear polysaccharide with 10% rhamnogalacturonan II has improved the As removal through urination by chelation for the reduction of the As in the body (Eliaz et al. 2006). Mehrandish et al. (2019) also reported medicinal plants including *Ginkgo biloba* (gingko), *Coriandrum sativum* (cilantro), *Allium sativum* (garlic), *Curcuma longa* (turmeric), *Silybum marianum* (milk thistle) and *Chlorophyta* (green algae) containing phytochelatins, herbal fibers, triphala and other compounds, which chelates the metals and could be a suitable potent treatment method for heavy metal poisoning.

Neurology related disorders

It is a well-known that with normal ageing, bio-metals (Fe, Zn, Cu) are accumulated in the brain (Kastenholz and Garfin 2009). There is growing evidence regarding the role of the disruption of cerebral bio-metal regulation in the etiology of Alzheimer’s disease, Parkinson’s disease, Wilson disease and other neurological disorders (Dusek and Aaseth 2016).

Alzheimer’s disease Among other features, neurodegeneration in Alzheimer’s disease (AD) is distinguished by the accumulation of metals (usually Fe, Al, Zn and Cu) in different parts of the brain (Speziali and Orvini 2003; Molina-Holgado et al. 2007) and the disruption of the metabolism of these metals leading to their modified transport and accumulation in plaques and other parts of the brain resulting in Alzheimer’s disease (Bishop et al. 2002).

Therapeutics that prevent biological damage from intra and extra-cellular metals by forming stable complexes with the metals, with less toxicity for the body, originating from natural sources have gained attention from most drug designers (Flora and Pachauri 2010; Lawson et al. 2016). Natural based flavonoids, sterols, carotenoids and phenolics as potent metal chelators, scavengers of free radicals, inhibitors of Fe^{2+} induced lipid peroxidation and protein oxidation (Pangestuti and Kim 2011). These chelators are useful for treating AD by protecting the cells from oxidative and nitrosative damage (Olasehinde et al. 2017).

Parkinson’s disease Studies discuss the role of iron metabolism dysregulation as an important pathological characteristic of Parkinson’s disease (Mandel et al. 2004). Iron chelation has been introduced as a favorable therapeutic method for the treatment of neurodegenerative diseases with features of iron overload including Parkinson’s disease. Epigallocatechin gallate with its strong iron chelating capabilities is known as having a neurodegenerative protection role and other associated disorders (Mandel et al. 2004).

Gao et al. (2012b) after 20–22 years of follow-up on more than 130,000 people concluded that it is less likely to develop Parkinson's disease with higher intakes of dietary flavonoids and their subclasses like anthocyanins, quercetin, epicatechin and some proanthocyanidins. Ginkgetin, which is a natural biflavonoid present in *Ginkgo biloba* leaves, can effectively chelate ferrous ions and subsequently avoid the enhancement of intracellular iron concentrations, contributing to neuroprotection used in the therapy for Parkinson's disease and other iron metabolism related disorders (Wang et al. 2015).

Conclusions

The threat of the application of hazardous materials in the metal related industry and finally the release of these materials in the environment is raising the importance of innovative environmentally friendly methods for different applications related to metals utilization, removal, recovery, etc. This paper reviews the most important plant metabolites with the capacity of binding to metals. Some of these compounds are present in considerable concentrations in plants and are usually grouped as phenols and polyphenols, alkaloids, saponins, proteins, amino acids, polysaccharide and organic acids. They have the capacity to interact with metals usually due to the possession of hydroxyl, carboxyl, carbonyl, amino groups, thiol groups, which contain atoms with lone pair electrons, that make them able to bind to different metals.

One of the most important characteristics of these compounds, that are supposed to be used for industrial applications, is their specificity and selectivity to interact with a certain type of metal. Although, some plant compounds have been identified with this feature, most of them lack selectivity, binding to a variety of metals. Some modifications of these compounds may increase their metal specification, or some of them can raise their metal interaction potential. There are several applications of plant-based metal interaction compounds in the industry, and other possibilities are still under research. Nevertheless, more investigation in this area is required to introduce suitable and safe compounds and their bearing plants for different industrial purposes. Additional research is also needed to modify the plant compounds, making them more metal-specific and to increase their efficiency and reusability. On the other hand, metal binding capacity, structure and characteristics of these compounds, can also inspire scientists to design and manufacture artificial compounds more selective in their interaction with metals.

Finally, it should be taken into account that extraction and purification of plant-based compounds can be difficult and very expensive as well as requiring relatively high quantities of organic solvents that may have negative effects on the ecosystems. The revised methods can be considered low-cost if they require few processing steps and/or the use of easily accessible plants abundant in nature, or plant wastes/by-products from other plant-based industries. Moreover, the stability and efficiency of these active constituents at high temperatures, high or low pH conditions and also in the presence of some chemical compounds may be decreased/inactivated. In severe conditions these compounds may be decomposed and thereby their relative efficiency may decrease. For these reasons, further studies are required in order to broaden and potentialize their application.

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References

Abbott AP, Boothby D, Capper G et al (2004) Deep eutectic solvents formed between choline chloride and carboxylic acids: versatile alternatives to ionic liquids. J Am Chem Soc 126:9142–9147. https://doi.org/10.1021/ja048266j

Abdel -Aty AM, Ammar NS, Abdel Ghafar HH, Ali RK (2013) Biosorption of cadmium and lead from aqueous solution by fresh water alga *Anabaena sphaerica* biomass. J Adv Res 4:367–374. https://doi.org/10.1016/j.jare.2012.07.004

Abdolali A, Guo WS, Ngo HH et al (2014) Typical lignocellulosic wastes and by-products for biosorption process in water and wastewater treatment: a critical review. Bioresour Technol 160:57–66. https://doi.org/10.1016/j.biortech.2013.12.037

Abdulrahman AS, Ismail M (2011) Green plant extract as a passivation-promoting inhibitor for reinforced concrete. Int J Eng Sci Technol 3:6484–6489

Abed el Aziz M, Ashour A, Madbouly H et al (2017) Investigations on green preparation of heavy metal saponin complexes. J Water Environ Nanotechnol. https://doi.org/10.22090/jwent.2017.02.005

Absalan G, Akhond M, Sheikhian L (2008) Extraction and high performance liquid chromatographic determination of 3-indole butyric acid in pea plants by using imidazolium-based ionic liquids as extractant. Talanta 77:407–411. https://doi.org/10.1016/j.talanta.2008.06.049

Achilonu MC, Umesiobi DO (2015) Bioactive phytochemicals: bioactivity, sources, preparations, and/or modifications via silver tetrafluoroborate mediation. J Chem 2015:1–22. https://doi.org/10.1155/2015/629085

Agnihotri A, Seth CS (2019) Transgenic brassicaceae. Transgenic plant technology for remediation of toxic metals and metalloids. Elsevier, Amsterdam, pp 239–255

Agwaramgbo L, Thomas C, GrayS C et al (2012) An evaluation of edible plant extracts for the phytoremediation of lead contaminated water. J Environ Prot 03:722–730. https://doi.org/10.4236/jep.2012.38086

Ahmad T (2014) Reviewing the tannic acid mediated synthesis of metal nanoparticles. J Nanotechnol 2014:1–11. https://doi.org/10.1155/2014/954206

Ahmed T, Gilani A-H, Abdollahi M et al (2015) Berberine and neurodegeneration: a review of literature. Pharmacol Rep 67:970–979. https://doi.org/10.1016/j.pharep.2015.03.002

Ajitha B, Ashok Kumar Reddy Y, Rajesh KM, Sreedhara Reddy P (2016) Sesbania grandiflora leaf extract assisted green synthesis of silver nanoparticles: antimicrobial activity. Mater Today Proc 3:1977–1984. https://doi.org/10.1016/j.matpr.2016.04.099

Akpomie KG, Dawodu FA, Adebowale KO (2015) Mechanism on the sorption of heavy metals from binary-solution by a low cost montmorillonite and its desorption potential. Alex Eng J 54:757–767. https://doi.org/10.1016/j.aej.2015.03.025

Alegria E, Ribeiro A, Mendes M et al (2018) Effect of phenolic compounds on the synthesis of gold nanoparticles and its catalytic activity in the reduction of nitro compounds. Nanomaterials 8:320. https://doi.org/10.3390/nano8050320

Al-Homaidan AA, Al-Qahtani HS, Al-Ghanayem AA et al (2018) Potential use of green algae as a biosorbent for hexavalent chromium removal from aqueous solutions. Saudi J Biol Sci 25:1733–1738. https://doi.org/10.1016/j.sjbs.2018.07.011

Ali S, Abbas Z, Seleiman MF et al (2020) Glycine betaine accumulation, significance and interests for heavy metal tolerance in plants. Plants 9:896. https://doi.org/10.3390/plants9070896

Aljabali A, Akkam Y, Al Zoubi M et al (2018) Synthesis of gold nanoparticles using leaf extract of *Ziziphus zizyphus* and their antimicrobial activity. Nanomaterials 8:174. https://doi.org/10.3390/nano8030174

Alvares Rodrigues L, Koibuchi Sakane K, Alves Nunes Simonetti E, Patrocínio Thim G (2015) Cr total removal in aqueous solution by PHENOTAN AP based tannin gel (TFC). J Environ Chem Eng 3:725–733. https://doi.org/10.1016/j.jece.2015.04.006

Andersen O (2004) Chemical and biological considerations in the treatment of metal intoxications by chelating agents. Mini-Rev Med Chem 4:11–21. https://doi.org/10.2174/1389557043487583

Anjum NA, Gill SS, Gill R (eds) (2013) Plant adaptation to environmental change: significance of amino acids and their derivatives. CABI, Boston

Anjum NA, Hasanuzzaman M, Hossain MA et al (2015) Jacks of metal/metalloid chelation trade in plants; an overview. Front Plant Sci. https://doi.org/10.3389/fpls.2015.00192

Ankamwar B, Chaudhary M, Sastry M (2005) Gold nanotriangles biologically synthesized using tamarind leaf extract and potential application in vapor sensing. Synth React Inorg Met-Org Nano-Met Chem 35:19–26. https://doi.org/10.1081/SIM-200047527

Arasaretnam S, Karunanayake L (2010) Synthesis, characterization, and metal adsorption properties of tannin-phenol-formaldehyde resins produced using tannin from dried fruit of *Terminalia chebula* (Aralu). J Appl Polym Sci 115:1081–1088. https://doi.org/10.1002/app.31098

Arbenz A, Avérous L (2015) Chemical modification of tannins to elaborate aromatic biobased macromolecular architectures. Green Chem 17:2626–2646. https://doi.org/10.1039/C5GC00282F

Aribo S, Olusegun SJ, Ibhadiyi LJ et al (2017) Green inhibitors for corrosion protection in acidizing oilfield environment. J Assoc Arab Univ Basic Appl Sci 24:34–38. https://doi.org/10.1016/j.jaubas.2016.08.001

Arwidsson Z, Elgh-Dalgren K, von Kronhelm T et al (2010) Remediation of heavy metal contaminated soil washing residues with amino polycarboxylic acids. J Hazard Mater 173:697–704. https://doi.org/10.1016/j.jhazmat.2009.08.141

Asipita SA, Ismail M, Majid MZA et al (2014) Green Bambusa Arundinacea leaves extract as a sustainable corrosion inhibitor in steel reinforced concrete. J Clean Prod 67:139–146. https://doi.org/10.1016/j.jclepro.2013.12.033

Aswathy Aromal S, Philip D (2012) Facile one-pot synthesis of gold nanoparticles using tannic acid and its application in catalysis. Phys E Low-Dimens Syst Nanostruct 44:1692–1696. https://doi.org/10.1016/j.physe.2012.04.022

Atarod M, Nasrollahzadeh M, Mohammad Sajadi S (2016) Green synthesis of Pd/RGO/Fe_3O_4 nanocomposite using Withania coagulans leaf extract and its application as magnetically separable and reusable catalyst for the reduction of 4-nitrophenol. J Colloid Interface Sci 465:249–258. https://doi.org/10.1016/j.jcis.2015.11.060

Ayangbenro A, Babalola O (2017) A new strategy for heavy metal polluted environments: a review of microbial biosorbents. Int J Environ Res Public Health 14:94. https://doi.org/10.3390/ijerph14010094

Aziz HA, Adlan MohdN, Ariffin KS (2008) Heavy metals (Cd, Pb, Zn, Ni, Cu and Cr(III)) removal from water in Malaysia: post treatment by high quality limestone. Bioresour Technol 99:1578–1583. https://doi.org/10.1016/j.biortech.2007.04.007

Baban KM, Milind BU (2011) Solution behavior of copper complexes with antibacterial drugs and amino acids. Der Chemica Sinica 2:158–164

Balaji DS, Basavaraja S, Deshpande R et al (2009) Extracellular biosynthesis of functionalized silver nanoparticles by strains of *Cladosporium cladosporioides* fungus. Colloids Surf B Biointerfaces 68:88–92. https://doi.org/10.1016/j.colsurfb.2008.09.022

Balandrin MF (1996) Commercial utilization of plant-derived saponins: an overview of medicinal, pharmaceutical, and industrial applications. In: Waller GR, Yamasaki K (eds) Saponins used in traditional and modern medicine. Springer US, Boston, pp 1–14

Baran EJ (2014) Review: natural oxalates and their analogous synthetic complexes. J Coord Chem 67:3734–3768. https://doi.org/10.1080/00958972.2014.937340

Barreira J, Ferreira I, Oliveira M, Pereira J (2008) Antioxidant activities of the extracts from chestnut flower, leaf, skins and fruit. Food Chem 107:1106–1113. https://doi.org/10.1016/j.foodchem.2007.09.030

Ben Harb M, Abubshait S, Etteyeb N et al (2020) Olive leaf extract as a green corrosion inhibitor of reinforced concrete contaminated with seawater. Arab J Chem 13:4846–4856. https://doi.org/10.1016/j.arabjc.2020.01.016

Bishop GM, Robinson SR, Liu Q et al (2002) Iron: a pathological mediator of Alzheimer disease? Dev Neurosci 24:184–187. https://doi.org/10.1159/000065696

Boratyński PJ, Zielińska-Błajet M, Skarżewski J (2019) Cinchona alkaloids—derivatives and applications. The alkaloids: chemistry and biology. Elsevier, Amsterdam, pp 29–145

Bota C, Deliu C, Creanga I (2011) The effect of copper sulphate on the production of flavonoids in digitalis lanata cell cultures. Farmacia 59:113–118

Bozin B, Mimica-Dukic N, Samojlik I et al (2008) Phenolics as antioxidants in garlic (*Allium sativum* L., Alliaceae). Food Chem 111:925–929. https://doi.org/10.1016/j.foodchem.2008.04.071

Bozorg M, Shahrabi Farahani T, Neshati J et al (2014) Myrtus communis as green inhibitor of copper corrosion in sulfuric acid. Ind Eng Chem Res 53:4295–4303. https://doi.org/10.1021/ie404056w

Brewer MS (2011) Natural antioxidants: sources, compounds, mechanisms of action, and potential applications. Compr Rev Food Sci Food Saf 10:221–247. https://doi.org/10.1111/j.1541-4337.2011.00156.x

Brown EJ, Khodr H, Hider CR, Rice-Evans CA (1998) Structural dependence of flavonoid interactions with Cu^{2+} ions: implications for their antioxidant properties. Biochem J 330:1173–1178. https://doi.org/10.1042/bj3301173

Çalişkan M (2000) The metabolism of oxalic acid. Turk J Zool 24:103–106

Castro-Vargas HI, Rodríguez-Varela LI, Ferreira SRS, Parada-Alfonso F (2010) Extraction of phenolic fraction from guava seeds (*Psidium guajava* L.) using supercritical carbon dioxide and co-solvents. J Supercrit Fluids 51:319–324. https://doi.org/10.1016/j.supflu.2009.10.012

Cataldo F, Angelini G (2013) A green synthesis of colloidal silver nanoparticles and their reaction with ozone. Eur Chem Bull 2:700–705. https://doi.org/10.17628/ecb.2013.2.700-705

Ćetković G, Savatović S, Čanadanović-Brunet J et al (2012) Valorisation of phenolic composition, antioxidant and cell growth activities of tomato waste. Food Chem 133:938–945. https://doi.org/10.1016/j.foodchem.2012.02.007

Chang CW, Anderson JU (1968) Flocculation of clays and soils by organic compounds. Soil Sci Soc Am J 32:23–27. https://doi.org/10.2136/sssaj1968.03615995003200010006x

Chaturvedula VSP, Prakash I (2011) The aroma, taste, color and bioactive constituents of tea. J Med Plants Res 5:2110–2124

Chen C-S, Zhang D, Wang Y-Q et al (2012) Effects of fruit bagging on the contents of phenolic compounds in the peel and flesh of 'Golden Delicious', 'Red Delicious', and 'Royal Gala' apples. Sci Hortic 142:68–73. https://doi.org/10.1016/j.scienta.2012.05.001

Chen S, Sahito ZA, Zhang M et al (2018) Identification and characterization of four nicotianamine synthase genes in *Sedum alfredii* Hance. J Biobased Mater Bioenergy 12:551–559. https://doi.org/10.1166/jbmb.2018.1803

Chen W-J, Hsiao L-C, Chen KK-Y (2008) Metal desorption from copper(II)/nickel(II)-spiked kaolin as a soil component using plant-derived saponin biosurfactant. Process Biochem 43:488–498. https://doi.org/10.1016/j.procbio.2007.11.017

Cheynier V, Comte G, Davies KM et al (2013) Plant phenolics: recent advances on their biosynthesis, genetics, and ecophysiology. Plant Physiol Biochem 72:1–20. https://doi.org/10.1016/j.plaphy.2013.05.009

Chin D, Means AR (2000) Calmodulin: a prototypical calcium sensor. Trends Cell Biol 10:322–328. https://doi.org/10.1016/S0962-8924(00)01800-6

Chlebda E, Magdalan J, Merwid-Ląd A et al (2010) Influence of water-soluble flavonoids, quercetin-5′-sulfonic acid sodium salt and morin-5′-sulfonic acid sodium salt, on antioxidant parameters in the subacute cadmium intoxication mouse model. Exp Toxicol Pathol 62:105–108. https://doi.org/10.1016/j.etp.2009.02.118

Chobot V, Hadacek F (2010) Iron and its complexation by phenolic cellular metabolites: from oxidative stress to chemical weapons. Plant Signal Behav 5:4–8. https://doi.org/10.4161/psb.5.1.10197

Choppala G, Saifullah, Bolan N et al (2014) Cellular mechanisms in higher plants governing tolerance to cadmium toxicity. Crit Rev Plant Sci 33:374–391. https://doi.org/10.1080/07352689.2014.903747

Choudhary BC, Paul D, Borse AU, Garole DJ (2017) Recovery of palladium from secondary waste using soluble tannins cross-linked *Lagerstroemia speciosa* leaves powder: recovery of palladium from secondary waste using biomass. J Chem Technol Biotechnol 92:1667–1677. https://doi.org/10.1002/jctb.5163

Ciesielski W, Lii C, Yen M-T, Tomasik P (2003) Interactions of starch with salts of metals from the transition groups. Carbohydr Polym 51:47–56. https://doi.org/10.1016/S0144-8617(02)00108-X

Clemens S (2001) Molecular mechanisms of plant metal tolerance and homeostasis. Planta 212:475–486. https://doi.org/10.1007/s004250000458

Cobbett C, Goldsbrough P (2002) PHYTOCHELATINS AND METALLOTHIONEINS: roles in heavy metal detoxification and homeostasis. Annu Rev Plant Biol 53:159–182. https://doi.org/10.1146/annurev.arplant.53.100301.135154

Cos P, Ying L, Calomme M et al (1998) Structure—activity relationship and classification of flavonoids as inhibitors of xanthine oxidase and superoxide scavengers. J Nat Prod 61:71–76. https://doi.org/10.1021/np970237h

Cotton FA, Cotton FA (eds) (1999) Advanced inorganic chemistry, 6th edn. Wiley, New York

Crini G (2005) Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment. Prog Polym Sci 30:38–70. https://doi.org/10.1016/j.progpolymsci.2004.11.002

Cui Y, Lai X, Liu K et al (2020) *Ginkgo biloba* leaf polysaccharide stabilized palladium nanoparticles with enhanced peroxidase-like property for the colorimetric detection of glucose. RSC Adv 10:7012–7018. https://doi.org/10.1039/D0RA00680G

Cvjetko Bubalo M, Vidović S, Radojčić Redovniković I, Jokić S (2018) New perspective in extraction of plant biologically active compounds by green solvents. Food Bioprod Process 109:52–73. https://doi.org/10.1016/j.fbp.2018.03.001

Das SK, Dickinson C, Lafir F et al (2012) Synthesis, characterization and catalytic activity of gold nanoparticles biosynthesized with *Rhizopus oryzae* protein extract. Green Chem 14:1322. https://doi.org/10.1039/c2gc16676c

de Jesus NZT, Falcão H, de Gomes S et al (2012) Tannins, peptic ulcers and related mechanisms. Int J Mol Sci 13:3203–3228. https://doi.org/10.3390/ijms13033203

de la Rosa LA, Moreno-Escamilla JO, Rodrigo-García J, Alvarez-Parrilla E (2019) Phenolic compounds. Postharvest physiology and biochemistry of fruits and vegetables. Elsevier, Amsterdam, pp 253–271

Debnath B, Singh WS, Das M et al (2018) Role of plant alkaloids on human health: a review of biological activities. Mater Today Chem 9:56–72. https://doi.org/10.1016/j.mtchem.2018.05.001

Del Valle EMM (2004) Cyclodextrins and their uses: a review. Process Biochem 39:1033–1046. https://doi.org/10.1016/S0032-9592(03)00258-9

Delangiz N, Khoshru B, Asgari Lajayer B et al (2020) Molecular mechanisms of heavy metal tolerance in plants. In: Faisal M, Saquib Q, Alatar AA, Al-Khedhairy AA et al (eds) Cellular and molecular phytotoxicity of heavy metals. Springer International Publishing, Cham, pp 125–136

Dermont G, Bergeron M, Mercier G, Richer-Laflèche M (2008) Soil washing for metal removal: a review of physical/chemical technologies and field applications. J Hazard Mater 152:1–31. https://doi.org/10.1016/j.jhazmat.2007.10.043

Desoky E-SM, Elrys AS, Rady MM (2019) Licorice root extract boosts *Capsicum annuum* L. production and reduces fruit contamination on a heavy metals-contaminated saline soil. Int Lett Nat Sci 73:1–16. https://doi.org/10.18052/www.scipress.com/ILNS.73.1

Devatha CP, Thalla AK, Katte SY (2016) Green synthesis of iron nanoparticles using different leaf extracts for treatment of domestic waste water. J Clean Prod 139:1425–1435. https://doi.org/10.1016/j.jclepro.2016.09.019

DiMauro EF, Mamai A, Kozlowski MC (2003) Synthesis, characterization, and metal complexes of a salen ligand containing a quinoline base. Organometallics 22:850–855. https://doi.org/10.1021/om0205795

Do QD, Angkawijaya AE, Tran-Nguyen PL et al (2014) Effect of extraction solvent on total phenol content, total flavonoid content, and antioxidant activity of *Limnophila aromatica*. J Food Drug Anal 22:296–302. https://doi.org/10.1016/j.jfda.2013.11.001

Du F-Y, Xiao X-H, Luo X-J, Li G-K (2009) Application of ionic liquids in the microwave-assisted extraction of polyphenolic compounds from medicinal plants. Talanta 78:1177–1184. https://doi.org/10.1016/j.talanta.2009.01.040

Durán M, Silveira CP, Durán N (2015) Catalytic role of traditional enzymes for biosynthesis of biogenic metallic nanoparticles: a mini-review. IET Nanobiotechnol 9:314–323. https://doi.org/10.1049/iet-nbt.2014.0054

Dusek P, Aaseth J (2016) Chelating therapy in metal storage diseases. Chelation therapy in the treatment of metal intoxication. Elsevier, Amsterdam, pp 285–311

Dwivedi AD, Dubey SP, Hokkanen S et al (2014) Recovery of gold from aqueous solutions by taurine modified cellulose: an adsorptive–reduction pathway. Chem Eng J 255:97–106. https://doi.org/10.1016/j.cej.2014.06.017

Dzah CS, Duan Y, Zhang H et al (2020) Latest developments in polyphenol recovery and purification from plant by-products: a review. Trends Food Sci Technol 99:375–388. https://doi.org/10.1016/j.tifs.2020.03.003

El-Aziza MMA (2018) Biochemical reactions for the removal of heavy metals from aqueous solutions. MOJ Bioorganic Org Chem. https://doi.org/10.15406/mojboc.2018.02.0078

Eliaz I, Hotchkiss AT, Fishman ML, Rode D (2006) The effect of modified citrus pectin on urinary excretion of toxic elements: MODIFIED CITRUS PECTIN AND HEAVY METAL CHELATION. Phytother Res 20:859–864. https://doi.org/10.1002/ptr.1953

El-Seedi HR, El-Shabasy RM, Khalifa SAM et al (2019) Metal nanoparticles fabricated by green chemistry using natural extracts: biosynthesis, mechanisms, and applications. RSC Adv 9:24539–24559. https://doi.org/10.1039/C9RA02225B

El-Seedi HR, Zahran M, Khalifa SAM, El-Kemary M (2016) Spectral characterisation of the silver nanoparticles biosynthesised using *Ambrosia maritima* plant. Micro Nano Lett 11:311–314. https://doi.org/10.1049/mnl.2015.0572

Fan J-P, Cao J, Zhang X-H et al (2012) Optimization of ionic liquid based ultrasonic assisted extraction of puerarin from Radix Puerariae Lobatae by response surface methodology. Food Chem 135:2299–2306. https://doi.org/10.1016/j.foodchem.2012.07.038

Fazary AE, Ju Y-H, Fawy KF et al (2017) Nicotine—metal ion interactions in solutions: potentiometric, cyclic voltammetry investigations and quantum chemical calculations. J Chem Thermodyn 112:283–292. https://doi.org/10.1016/j.jct.2017.05.024

Felipe MBMC, Silva DR, Martinez-Huitle CA et al (2013) Effectiveness of *Croton cajucara* Benth on corrosion inhibition of carbon steel in saline medium: anti-corrosion effectiveness of *C. cajucara*. Mater Corros 64:530–534. https://doi.org/10.1002/maco.201206532

Fenwick GR, Price KR, Tsukamoto C, Okubo K (1991) Saponins. Toxic substances in crop plants. Elsevier, Amsterdam, pp 285–327

Ferrero AL, Walsh PR, Rajakaruna N (2020) The ecophysiology, genetics, adaptive significance, and biotechnology of nickel hyperaccumulation in plants. Physiological and biotechnological aspects of extremophiles. Elsevier, Amsterdam, pp 327–347

Fiol N, Escudero C, Poch J, Villaescusa I (2006) Preliminary studies on Cr(VI) removal from aqueous solution using grape stalk wastes encapsulated in calcium alginate beads in a packed bed up-flow column. React Funct Polym 66:795–807. https://doi.org/10.1016/j.reactfunctpolym.2005.11.006

Flora SJS, Pachauri V (2010) Chelation in metal intoxication. Int J Environ Res Public Health 7:2745–2788. https://doi.org/10.3390/ijerph7072745

Fosmire GJ (1990) Zinc toxicity. Am J Clin Nutr 51:225–227. https://doi.org/10.1093/ajcn/51.2.225

Francis G, Kerem Z, Makkar HPS, Becker K (2002) The biological action of saponins in animal systems: a review. Br J Nutr 88:587–605. https://doi.org/10.1079/BJN2002725

Freisinger E (2011) Structural features specific to plant metallothioneins. JBIC J Biol Inorg Chem 16:1035–1045. https://doi.org/10.1007/s00775-011-0801-z

Gao L, Kano N, Sato Y et al (2012) Behavior and distribution of heavy metals including rare earth elements, thorium, and uranium in sludge from industry water treatment plant and recovery method of metals by biosurfactants application. Bioinorg Chem Appl 2012:1–11. https://doi.org/10.1155/2012/173819

Gao X, Cassidy A, Schwarzschild MA et al (2012) Habitual intake of dietary flavonoids and risk of Parkinson disease. Neurology 78:1138–1145. https://doi.org/10.1212/WNL.0b013e31824f7fc4

Garcia-Salas P, Morales-Soto A, Segura-Carretero A, Fernández-Gutiérrez A (2010) Phenolic-compound-extraction systems for fruit and vegetable samples. Molecules 15:8813–8826. https://doi.org/10.3390/molecules15128813

Gatew S, Mersha W (2015) Tannery wastes water treatment using *Moringa Stenopetala* seed extract. Glob J Environ Sci 12:29. https://doi.org/10.4314/gjes.v12i1.4

Gill SS, Anjum NA, Gill R (2014) Target osmoprotectants for abiotic stress tolerance in crop plants—glycine betaine and proline. In: Anjum NA, Gill SS, Gill R (eds) Plant adaptation to environmental change: significance of amino acids and their derivatives. CABI, Wallingford, pp 97–108

Gobara M, Zaghloul B, Baraka A et al (2017) Green corrosion inhibition of mild steel to aqueous sulfuric acid by the extract of *Corchorus olitorius* stems. Mater Res Express 4:046504. https://doi.org/10.1088/2053-1591/aa664a

Godbold DL, Horst WJ, Collins JC et al (1984) Accumulation of zinc and organic acids in roots of zinc tolerant and non-tolerant ecotypes of *Deschampsia caespitosa*. J Plant Physiol 116:59–69. https://doi.org/10.1016/S0176-1617(84)80084-X

Gomes PF, Lennartsson PR, Persson N-K, Taherzadeh MJ (2014) Heavy metal biosorption by *Rhizopus* Sp. biomass immobilized on textiles. Water Air Soil Pollut 225:1834. https://doi.org/10.1007/s11270-013-1834-4

González-Guerrero M, Escudero V, Saéz Á, Tejada-Jiménez M (2016) Transition metal transport in plants and associated endosymbionts: arbuscular mycorrhizal fungi and rhizobia. Front Plant Sci. https://doi.org/10.3389/fpls.2016.01088

Gonzalez-Valdez LS, Almaraz-Abarca N, Proal-Nájera JB et al (2013) Surfactant properties of the saponins of *Agave durangensis*, application on arsenic removal. Int J Eng App Sci 4:8269

Grinberg LN, Newmark H, Kitrossky N et al (1997) Protective effects of tea polyphenols against oxidative damage to red blood cells. Biochem Pharmacol 54:973–978. https://doi.org/10.1016/S0006-2952(97)00155-X

Guo H, Wang W, Sun Y et al (2010) Ethyl lactate enhances ethylenediaminedisuccinic acid solution removal of copper from contaminated soils. J Hazard Mater 174:59–63. https://doi.org/10.1016/j.jhazmat.2009.09.016

Gupta KK, Taneja SC, Dhar KL, Atal CK (1983) Flavonoids of andrographis paniculata. Phytochemistry 22:314–315. https://doi.org/10.1016/S0031-9422(00)80122-3

Gurung M, Adhikari BB, Gao X et al (2014) Sustainability in the metallurgical industry: chemically modified cellulose for selective biosorption of gold from mixtures of base metals in chloride media. Ind Eng Chem Res 53:8565–8576. https://doi.org/10.1021/ie403203g

Gurung M, Adhikari BB, Morisada S et al (2013) N-aminoguanidine modified persimmon tannin: a new sustainable material for selective adsorption, preconcentration and recovery of precious metals from acidic chloride solution. Bioresour Technol 129:108–117. https://doi.org/10.1016/j.biortech.2012.11.012

Gusiatin ZM, Klimiuk E (2012) Metal (Cu, Cd and Zn) removal and stabilization during multiple soil washing by saponin. Chemosphere 86:383–391. https://doi.org/10.1016/j.chemosphere.2011.10.027

Halysh V, Trus I, Gomelya M et al (2020) Utilization of modified biosorbents based on walnut shells in the processes of wastewater treatment from heavy metal ion. J Ecol Eng 21:128–133. https://doi.org/10.12911/22998993/119809

Hammaini A, González F, Ballester A et al (2003) Simultaneous uptake of metals by activated sludge. Miner Eng 16:723–729. https://doi.org/10.1016/S0892-6875(03)00166-3

Hamouda RA, Hussein MH, Abo-elmagd RA, Bawazir SS (2019) Synthesis and biological characterization of silver nanoparticles derived from the cyanobacterium *Oscillatoria limnetica*. Sci Rep 9:13071. https://doi.org/10.1038/s41598-019-49444-y

Han S, Hong S-P, Kang E et al (2019) Iron gall ink revisited: natural formulation for black hair-dyeing. Cosmetics 6:23. https://doi.org/10.3390/cosmetics6020023

Hasanuzzaman M, Fujita M (2013) Exogenous sodium nitroprusside alleviates arsenic-induced oxidative stress in wheat (*Triticum aestivum* L.) seedlings by enhancing antioxidant defense and glyoxalase system. Ecotoxicology 22:584–596. https://doi.org/10.1007/s10646-013-1050-4

Hassinen VH, Tervahauta AI, Schat H, Kärenlampi SO (2011) Plant metallothioneins—metal chelators with ROS scavenging activity?: Plant metallothioneins. Plant Biol 13:225–232. https://doi.org/10.1111/j.1438-8677.2010.00398.x

Hefter GT, North NA, Tan SH (1997) Organic corrosion inhibitors in neutral solutions; part 1—inhibition of steel, copper, and aluminum by straight chain carboxylates. CORROSION 53:657–667. https://doi.org/10.5006/1.3290298

Hegde ML, Bharathi P, Suram A et al (2009) Challenges associated with metal chelation therapy in Alzheimer's disease. J Alzheimers Dis 17:457–468. https://doi.org/10.3233/JAD-2009-1068

Higdon JV, Frei B (2003) Tea catechins and polyphenols: health effects, metabolism, and antioxidant functions. Crit Rev Food Sci Nutr 43:89–143. https://doi.org/10.1080/10408690390826464

Hoffmann J, Nüchter M, Ondruschka B, Wasserscheid P (2003) Ionic liquids and their heating behaviour during microwave irradiation—a state of the art report and challenge to assessment. Green Chem 5:296–299. https://doi.org/10.1039/B212533A

Hong-Bo S, Li-Ye C, Cheng-Jiang R et al (2010) Understanding molecular mechanisms for improving phytoremediation of heavy metal-contaminated soils. Crit Rev Biotechnol 30:23–30. https://doi.org/10.3109/07388550903208057

Hossain MA, Burritt DJ, Fujita M (2015) Proline and glycine betaine modulate cadmium-induced oxidative stress tolerance in plants: Possible biochemical and molecular mechanisms. In: Azooz MM, Ahmad P (eds) Plant—environment interaction. Wiley, Chichester, pp 97–123

Hostettmann K, Marston A (1995) Saponins, 1st edn. Cambridge University Press, Cambridge

Huang J, Li Q, Sun D et al (2007) Biosynthesis of silver and gold nanoparticles by novel sundried *Cinnamomum camphora* leaf. Nanotechnology 18:105104. https://doi.org/10.1088/0957-4484/18/10/105104

Huang W, Liu Z (2013) Biosorption of Cd(II)/Pb(II) from aqueous solution by biosurfactant-producing bacteria: isotherm kinetic characteristic and mechanism studies. Colloids Surf B Biointerfaces 105:113–119. https://doi.org/10.1016/j.colsurfb.2012.12.040

Huang Y, Feng F, Jiang J et al (2017) Green and efficient extraction of rutin from tartary buckwheat hull by using natural deep eutectic solvents. Food Chem 221:1400–1405. https://doi.org/10.1016/j.foodchem.2016.11.013

Inoue K, Paudyal H, Nakagawa H et al (2010) Selective adsorption of chromium(VI) from zinc(II) and other metal ions using persimmon waste gel. Hydrometallurgy 104:123–128. https://doi.org/10.1016/j.hydromet.2010.05.005

Iravani S (2011) Green synthesis of metal nanoparticles using plants. Green Chem 13:2638. https://doi.org/10.1039/c1gc15386b

Irshad MA, Nawaz R, Zia ur Rehman M et al (2020) Synthesis and characterization of titanium dioxide nanoparticles by chemical and green methods and their antifungal activities against wheat rust. Chemosphere 258:127352. https://doi.org/10.1016/j.chemosphere.2020.127352

Irtelli B, Petrucci WA, Navari-Izzo F (2009) Nicotianamine and histidine/proline are, respectively, the most important copper chelators in xylem sap of *Brassica carinata* under conditions of copper deficiency and excess. J Exp Bot 60:269–277. https://doi.org/10.1093/jxb/ern286

Jain CK, Malik DS, Yadav AK (2016) Applicability of plant based biosorbents in the removal of heavy metals: a review. Environ Process 3:495–523. https://doi.org/10.1007/s40710-016-0143-5

Jain N, Bhargava A, Majumdar S et al (2011) Extracellular biosynthesis and characterization of silver nanoparticles using *Aspergillus flavus* NJP08: a mechanism perspective. Nanoscale 3:635–641. https://doi.org/10.1039/C0NR00656D

Jasiewicz B (2009) Sparteine and α-isosparteine complexes with Zn(II) and Cu(II): structure and spectroscopic properties. Mini-Rev Org Chem 6:275–282. https://doi.org/10.2174/157019309789371622

Jiang Z-M, Wang L-J, Gao Z et al (2019) Green and efficient extraction of different types of bioactive alkaloids using deep eutectic solvents. Microchem J 145:345–353. https://doi.org/10.1016/j.microc.2018.10.057

Jovanovic SV, Simic MG, Steenken S, Hara Y (1998) Iron complexes of gallocatechins. Antioxidant action or iron regulation? J Chem Soc Perkin Trans 2:2365–2370. https://doi.org/10.1039/a805894f

Kanamarlapudi SLRK, Chintalpudi VK, Muddada S (2018) Application of biosorption for removal of heavy metals from wastewater. In: Derco J, Vrana B (eds) Biosorption. InTech, London

Karamać M, Pegg RB (2009) Limitations of the tetramethylmurexide assay for investigating the Fe(II) chelation activity of phenolic compounds. J Agric Food Chem 57:6425–6431. https://doi.org/10.1021/jf901100t

Kastenholz B, Garfin D (2009) Medicinal plants: a natural chaperones source for treating neurological disorders. Protein Pept Lett 16:116–120. https://doi.org/10.2174/092986609787316234

Kasthuri J, Veerapandian S, Rajendiran N (2009) Biological synthesis of silver and gold nanoparticles using apiin as reducing agent. Colloids Surf B Biointerfaces 68:55–60. https://doi.org/10.1016/j.colsurfb.2008.09.021

Kaurinovic B, Vastag D (2019) Flavonoids and phenolic acids as potential natural antioxidants. In: Shalaby E (ed) Antioxidants. IntechOpen, London

Kavitha S, Dhamodaran M, Prasad R, Ganesan M (2017) Synthesis and characterisation of zinc oxide nanoparticles using terpenoid fractions of *Andrographis paniculata* leaves. Int Nano Lett 7:141–147. https://doi.org/10.1007/s40089-017-0207-1

Keerthana S, Abilasha R, Saraswathi K, Arumugam P (2019) Antioxidant and antibacterial natural products evaluation from terrestrial streptomyces species strain KAV 2 isolated from rhizosphere regions of *Piper betle*. J Drug Deliv Ther 9:26–37. https://doi.org/10.22270/jddt.v9i4-A.3390

Kelly-Vargas K, Cerro-Lopez M, Reyna-Tellez S et al (2012) Biosorption of heavy metals in polluted water, using different waste fruit cortex. Phys Chem Earth Parts ABC 37–39:26–29. https://doi.org/10.1016/j.pce.2011.03.006

Khan M, Albalawi GH, Shaik MR et al (2017) Miswak mediated green synthesized palladium nanoparticles as effective catalysts for the Suzuki coupling reactions in aqueous media. J Saudi Chem Soc 21:450–457. https://doi.org/10.1016/j.jscs.2016.03.008

Khan T-M, Gul NS, Lu X et al (2019) Rhodium(iii) complexes with isoquinoline derivatives as potential anticancer agents: in vitro and in vivo activity studies. Dalton Trans 48:11469–11479. https://doi.org/10.1039/C9DT01951K

Khanbabaee K, van Ree T (2001) Tannins: classification and definition. Nat Prod Rep 18:641–649. https://doi.org/10.1039/b1010611

Khandelwal S, Tailor YK, Kumar M (2016) Deep eutectic solvents (DESs) as eco-friendly and sustainable solvent/catalyst systems in organic transformations. J Mol Liq 215:345–386. https://doi.org/10.1016/j.molliq.2015.12.015

Kidd PS, Llugany M, Poschenrieder C et al (2001) The role of root exudates in aluminium resistance and silicon-induced amelioration of aluminium toxicity in three varieties of maize (*Zea mays* L.). J Exp Bot 52:1339–1352. https://doi.org/10.1093/jexbot/52.359.1339

Kiliç E, Font J, Puig R et al (2011) Chromium recovery from tannery sludge with saponin and oxidative remediation. J Hazard Mater 185:456–462. https://doi.org/10.1016/j.jhazmat.2010.09.054

Kim BS, Lim S-T (1999) Removal of heavy metal ions from water by cross-linked carboxymethyl corn starch. Carbohydr Polym 39:217–223. https://doi.org/10.1016/S0144-8617(99)00011-9

Kim J-J, Kim Y-S, Kumar V (2019) Heavy metal toxicity: an update of chelating therapeutic strategies. J Trace Elem Med Biol 54:226–231. https://doi.org/10.1016/j.jtemb.2019.05.003

Kim KD, Han DN, Kim HT (2004) Optimization of experimental conditions based on the Taguchi robust design for the formation of nano-sized silver particles by chemical reduction method. Chem Eng J 104:55–61. https://doi.org/10.1016/j.cej.2004.08.003

Kim Y-H, Ogata T, Nakano Y (2007) Kinetic analysis of palladium(II) adsorption process on condensed-tannin gel based on redox reaction models. Water Res 41:3043–3050. https://doi.org/10.1016/j.watres.2007.02.016

Kim Y-J, Kim S-O, Kim Y-I, Choi S-N (2001) A mimic molecule of blue copper protein active site [(–)-Sparteine-*N*, *N* ′](maleonitriledithiolato- *S*, *S* ′)copper(II). Inorg Chem 40:4481–4484. https://doi.org/10.1021/ic001396i

Kok Seng L (2018) Adsorption of heavy metals using banana peels in wastewater treatment. Eurasia Proc Sci Technol Eng Math 2:312–317

Kostyuk VA, Potapovich AI, Strigunova EN et al (2004) Experimental evidence that flavonoid metal complexes may act as mimics of superoxide dismutase. Arch Biochem Biophys 428:204–208. https://doi.org/10.1016/j.abb.2004.06.008

Kováčik J, Klejdus B, Hedbavny J (2010) Effect of aluminium uptake on physiology, phenols and amino acids in *Matricaria chamomilla* plants. J Hazard Mater 178:949–955. https://doi.org/10.1016/j.jhazmat.2010.02.029

Krämer U, Cotter-Howells JD, Charnock JM et al (1996) Free histidine as a metal chelator in plants that accumulate nickel. Nature 379:635–638. https://doi.org/10.1038/379635a0

Kraus TEC, Dahlgren RA, Zasoski RJ (2003) Tannins in nutrient dynamics of forest ecosystems—a review. Plant Soil 256:41–66. https://doi.org/10.1023/A:1026206511084

Kregiel D, Berlowska J, Witonska I et al (2017) Saponin-based, biological-active surfactants from plants. In: Najjar R (ed) Application and characterization of surfactants. InTech, London

Kulbat K (2016) The role of phenolic compounds in plant resistance. Biotechnol Food Sci 80:97–108

Kundu M, Prasad SK, Virendra K (2016) A review article on green inhibitors of reinforcement concrete corrosion. Int J Emerging Res Manag Tech 5:42–46

Kusmierek E, Chrzescijanska E (2015) Tannic acid as corrosion inhibitor for metals and alloys: tannic acid as corrosion inhibitor. Mater Corros 66:169–174. https://doi.org/10.1002/maco.201307277

Kutrowska A, Szelag M (2014) Low-molecular weight organic acids and peptides involved in the long-distance transport of trace metals. Acta Physiol Plant 36:1957–1968. https://doi.org/10.1007/s11738-014-1576-y

Küünal S, Rauwel P, Rauwel E (2018) Plant extract mediated synthesis of nanoparticles. Emerging applications of nanoparticles and architecture nanostructures. Elsevier, Amsterdam, pp 411–446

Kweon D-K, Choi J-K, Kim E-K, Lim S-T (2001) Adsorption of divalent metal ions by succinylated and oxidized corn starches. Carbohydr Polym 46:171–177. https://doi.org/10.1016/S0144-8617(00)00300-3

Lathan N, Edwards S, Thomas C, Agwaramgbo L (2013) Comparative study of lead removal by extracts of spinach, coffee, and tea. J Environ Prot 04:250–257. https://doi.org/10.4236/jep.2013.43029

Laurie S (1995) Handbook of metal-ligand interactions in biological fluids. Bioinorganic chemistry. Marcel Dekker, New York

Lavid N, Schwartz A, Yarden O, Tel-Or E (2001) The involvement of polyphenols and peroxidase activities in heavy-metal accumulation by epidermal glands of the waterlily (Nymphaeaceae). Planta 212:323–331. https://doi.org/10.1007/s004250000400

Lawson MK, Valko M, Cronin MTD, Jomová K (2016) Chelators in iron and copper toxicity. Curr Pharmacol Rep 2:271–280. https://doi.org/10.1007/s40495-016-0068-8

Lebrini M, Suedile F, Salvin P et al (2020) Bagassa guianensis ethanol extract used as sustainable eco-friendly inhibitor for zinc corrosion in 3% NaCl: electrochemical and XPS studies. Surf Interfaces 20:100588. https://doi.org/10.1016/j.surfin.2020.100588

Lee J, Cho H, Choi J et al (2015) Chemical sporulation and germination: cytoprotective nanocoating of individual mammalian cells with a degradable tannic acid–Fe^{III} complex. Nanoscale 7:18918–18922. https://doi.org/10.1039/C5NR05573C

Lee YA, Lee J, Kim DW et al (2017) Mussel-inspired surface functionalization of porous carbon nanosheets using polydopamine and Fe^{3+}/tannic acid layers for high-performance electrochemical capacitors. J Mater Chem A 5:25368–25377. https://doi.org/10.1039/C7TA08010G

Leszczyszyn OI, Imam HT, Blindauer CA (2013) Diversity and distribution of plant metallothioneins: a review of structure, properties and functions. Metallomics 5:1146. https://doi.org/10.1039/c3mt00072a

Levites Y, Weinreb O, Maor G et al (2001) Green tea polyphenol (-)-epigallocatechin-3-gallate prevents N-methyl-4-phenyl-1,2,3,6-tetrahydropyridine-induced dopaminergic neurodegeneration: EGCG prevents MPTP-induced neurodegeneration. J Neurochem 78:1073–1082. https://doi.org/10.1046/j.1471-4159.2001.00490.x

Li H, Dong X, da Silva EB et al (2017) Mechanisms of metal sorption by biochars: biochar characteristics and modifications. Chemosphere 178:466–478. https://doi.org/10.1016/j.chemosphere.2017.03.072

Li H, Shi W, Shao H, Shao M (2009) The remediation of the lead-polluted garden soil by natural zeolite. J Hazard Mater 169:1106–1111. https://doi.org/10.1016/j.jhazmat.2009.04.067

Li H-J, Zhang W, Wu Y-C (2019) Anti-corrosive properties of alkaloids on metals. In: Kurek J (ed) Alkaloids—their importance in nature and human life. IntechOpen, London

Li W, He Q, Zhang S et al (2008) Some new triazole derivatives as inhibitors for mild steel corrosion in acidic medium. J Appl Electrochem 38:289–295. https://doi.org/10.1007/s10800-007-9437-7

Libert B, Franceschi VR (1987) Oxalate in crop plants. J Agric Food Chem 35:926–938. https://doi.org/10.1021/jf00078a019

Liu B, Wang D, Yu G, Meng X (2013) Adsorption of heavy metal ions, dyes and proteins by chitosan composites and derivatives—a review. J Ocean Univ China 12:500–508. https://doi.org/10.1007/s11802-013-2113-0

Liu Y-S, Chang Y-C, Chen H-H (2018) Silver nanoparticle biosynthesis by using phenolic acids in rice husk extract as reducing agents and dispersants. J Food Drug Anal 26:649–656. https://doi.org/10.1016/j.jfda.2017.07.005

López M, Martínez F, Del Valle C et al (2001) Analysis of phenolic constituents of biological interest in red wines by high-performance liquid chromatography. J Chromatogr A 922:359–363. https://doi.org/10.1016/S0021-9673(01)00913-X

Lopez-Lazaro M (2009) Distribution and biological activities of the flavonoid luteolin. Mini-Rev Med Chem 9:31–59. https://doi.org/10.2174/138955709787001712

Louis H, Maitera ON, Barminas JT, Akakuru OU, Boro G (2018) Synthesis and characterization of some metal complexes using herbal flavonoids. Nat Prod Chem Res. https://doi.org/10.4172/2329-6836.1000314

Lu Y, Ma W, Hu R et al (2008) Ionic liquid-based microwave-assisted extraction of phenolic alkaloids from the medicinal plant *Nelumbo nucifera* Gaertn. J Chromatogr A 1208:42–46. https://doi.org/10.1016/j.chroma.2008.08.070

Ma Y, Oliveira RS, Freitas H, Zhang C (2016) Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. Front Plant Sci. https://doi.org/10.3389/fpls.2016.00918

Maheswaran H, Prasanth KL, Krishna GG et al (2006) Enantioselective nitroaldol (Henry) reaction using copper(ii) complexes of (–)-sparteine. Chem Commun. https://doi.org/10.1039/B610203D

Mahmood S, Jameel S, Department of Chemistry, Division of Science & Technology, University of Education, Township Campus, Lahore, Pakistan et al (2018) Isolation, purification and complex formation of nicotine alkaloid. Eng Appl Sci Lett. https://doi.org/10.30538/psrp-easl2018.0009

Maity JP, Huang YM, Hsu C-M et al (2013) Removal of Cu, Pb and Zn by foam fractionation and a soil washing process from contaminated industrial soils using soapberry-derived saponin: a comparative effectiveness assessment. Chemosphere 92:1286–1293. https://doi.org/10.1016/j.chemosphere.2013.04.060

Makarov VV, Love AJ, Sinitsyna OV et al (2014) "Green" nanotechnologies: synthesis of metal nanoparticles using plants. Acta Naturae 6:35–44

Manach C, Scalbert A, Morand C et al (2004) Polyphenols: food sources and bioavailability. Am J Clin Nutr 79:727–747. https://doi.org/10.1093/ajcn/79.5.727

Mandel S, Maor G, Youdim MBH (2004) Iron and α-synuclein in the substantia Nigra of MPTP-treated mice: effect of neuroprotective drugs R-apomorphine and green tea polyphenol (-)-epigallocatechin-3-gallate. J Mol Neurosci 24:401–416. https://doi.org/10.1385/JMN:24:3:401

Marslin G, Siram K, Maqbool Q et al (2018) Secondary metabolites in the green synthesis of metallic nanoparticles. Materials 11:940. https://doi.org/10.3390/ma11060940

Martínez-Cabanas M, López-García M, Barriada JL et al (2016) Green synthesis of iron oxide nanoparticles. Development of magnetic hybrid materials for efficient As(V) removal. Chem Eng J 301:83–91. https://doi.org/10.1016/j.cej.2016.04.149

Maruyama T, Matsushita H, Shimada Y et al (2007) Proteins and protein-rich biomass as environmentally friendly adsorbents selective for precious metal ions. Environ Sci Technol 41:1359–1364. https://doi.org/10.1021/es061664x

Massabni AC, Corbi PP, Melnikov P et al (2005) Four new metal complexes with the amino acid deoxyalliin. J Braz Chem Soc 16:718–722. https://doi.org/10.1590/S0103-50532005000500006

McDonald M, Mila I, Scalbert A (1996) Precipitation of metal ions by plant polyphenols: optimal conditions and origin of precipitation. J Agric Food Chem 44:599–606. https://doi.org/10.1021/jf950459q

Md Ishak NAI, Kamarudin SK, Timmiati SN (2019) Green synthesis of metal and metal oxide nanoparticles via plant extracts: an overview. Mater Res Express 6:112004. https://doi.org/10.1088/2053-1591/ab4458

Medina-Torres N, Ayora-Talavera T, Espinosa-Andrews H et al (2017) Ultrasound assisted extraction for the recovery of phenolic compounds from vegetable sources. Agronomy 7:47. https://doi.org/10.3390/agronomy7030047

Meethale Kunnambath P, Thirumalaisamy S (2015) Characterization and utilization of tannin extract for the selective adsorption of Ni (II) ions from water. J Chem 2015:1–9. https://doi.org/10.1155/2015/498359

Mehes-Smith M, Nkongolo K, Cholew E (2013) Coping mechanisms of plants to metal contaminated soil. In: Silvern S (ed) Environmental change and sustainability. InTech, London

Mehrandish R, Rahimian A, Shahriary A (2019) Heavy metals detoxification: a review of herbal compounds for chelation therapy in heavy metals toxicity. J Herbmed Pharmacol 8:69–77. https://doi.org/10.15171/jhp.2019.12

Mejáre M, Bülow L (2001) Metal-binding proteins and peptides in bioremediation and phytoremediation of heavy metals. Trends Biotechnol 19:67–73. https://doi.org/10.1016/S0167-7799(00)01534-1

Michalak A (2006) Phenolic compounds and their antioxidant activity in plants growing under heavy metal stress. Pol J Environ Stud 15:523–530

Mila I, Scalbert A, Expert D (1996) Iron withholding by plant polyphenols and resistance to pathogens and rots. Phytochemistry 42:1551–1555. https://doi.org/10.1016/0031-9422(96)00174-4

Milić BL, Djilas SM, Čanadanović-Brunet JM (1998) Antioxidative activity of phenolic compounds on the metal-ion breakdown of lipid peroxidation system. Food Chem 61:443–447. https://doi.org/10.1016/S0308-8146(97)00126-X

Mittal AK, Chisti Y, Banerjee UC (2013) Synthesis of metallic nanoparticles using plant extracts. Biotechnol Adv 31:346–356. https://doi.org/10.1016/j.biotechadv.2013.01.003

Mohamad NAN, Arham NA, Jai J, Hadi A (2013) Plant extract as reducing agent in synthesis of metallic nanoparticles: a review. Adv Mater Res 832:350–355. https://doi.org/10.4028/www.scientific.net/AMR.832.350

Mohan S, Singh Y, Verma DK, Hasan SH (2015) Synthesis of CuO nanoparticles through green route using Citrus limon juice and its application as nanosorbent for Cr(VI) remediation: process optimization with RSM and ANN-GA based model. Process Saf Environ Prot 96:156–166. https://doi.org/10.1016/j.psep.2015.05.005

Molina-Holgado F, Hider RC, Gaeta A et al (2007) Metals ions and neurodegeneration. Biometals 20:639–654. https://doi.org/10.1007/s10534-006-9033-z

Mongkhonsin B, Nakbanpote W, Hokura A et al (2016) Phenolic compounds responding to zinc and/or cadmium treatments in *Gynura pseudochina* (L.) DC. extracts and biomass. Plant Physiol Biochem 109:549–560. https://doi.org/10.1016/j.plaphy.2016.10.027

Monsant AC, Kappen P, Wang Y et al (2011) In vivo speciation of zinc in *Noccaea caerulescens* in response to nitrogen form and zinc exposure. Plant Soil 348:167–183. https://doi.org/10.1007/s11104-011-0887-7

Montazer-Rahmati MM, Rabbani P, Abdolali A, Keshtkar AR (2011) Kinetics and equilibrium studies on biosorption of cadmium, lead, and nickel ions from aqueous solutions by intact and chemically modified brown algae. J Hazard Mater 185:401–407. https://doi.org/10.1016/j.jhazmat.2010.09.047

Morales F, Pavlovič A, Abadía A, Abadía J (2018) Photosynthesis in poor nutrient soils, in compacted soils, and under drought. In: Adams IIIWW, Terashima I (eds) The leaf: a platform for performing photosynthesis. Springer International Publishing, Cham, pp 371–399

Morisada S, Kim Y-H, Ogata T et al (2011) Improved adsorption behaviors of amine-modified tannin gel for palladium and platinum ions in acidic chloride solutions. Ind Eng Chem Res 50:1875–1880. https://doi.org/10.1021/ie102193a

Moura ECM de, Souza ADN, Rossi CGFT et al (2013) Avaliação do potencial anticorrosivo de tiossemicarbazonas solubilizadas em microemulsão. Quím Nova 36:59–62. https://doi.org/10.1590/S0100-40422013000100011

Mukhopadhyay S, Mukherjee S, Hashim MA et al (2018) Zinc removal from soil by washing with saponin obtained from *Sapindus mukorossi*. J Environ Anal Chem. https://doi.org/10.4172/2380-2391.1000249

Munichandran M, Gangadhar B, Latha P, Ramakrishna Naidu G (2016) Studies on the reduction of lead and cadmium from aqueous solutions using citrus pennivesiculata (Gajanimma) peel. J App Chem 5:488–496

Mystrioti C, Xanthopoulou TD, Tsakiridis P et al (2016) Comparative evaluation of five plant extracts and juices for nanoiron synthesis and application for hexavalent chromium reduction. Sci Total Environ 539:105–113. https://doi.org/10.1016/j.scitotenv.2015.08.091

Naika HR, Lingaraju K, Manjunath K et al (2015) Green synthesis of CuO nanoparticles using *Gloriosa superba* L. extract and their antibacterial activity. J Taibah Univ Sci 9:7–12. https://doi.org/10.1016/j.jtusci.2014.04.006

Nakano Y, Takeshita K, Tsutsumi T (2001) Adsorption mechanism of hexavalent chromium by redox within condensed-tannin gel. Water Res 35:496–500. https://doi.org/10.1016/S0043-1354(00)00279-7

Nasernejad B, Zadeh TE, Pour BB et al (2005) Camparison for biosorption modeling of heavy metals (Cr (III), Cu (II), Zn (II)) adsorption from wastewater by carrot residues. Process Biochem 40:1319–1322. https://doi.org/10.1016/j.procbio.2004.06.010

Nasrollahzadeh M, Mohammad Sajadi S (2015) Green synthesis of copper nanoparticles using *Ginkgo biloba* L. leaf extract and their catalytic activity for the Huisgen [3 + 2] cycloaddition of azides and alkynes at room temperature. J Colloid Interface Sci 457:141–147. https://doi.org/10.1016/j.jcis.2015.07.004

Nasrollahzadeh M, Sajadi SM (2015) Preparation of Au nanoparticles by *Anthemis xylopoda* flowers aqueous extract and their application for alkyne/aldehyde/amine A^3-type coupling reactions. RSC Adv 5:46240–46246. https://doi.org/10.1039/C5RA08927A

Nasrollahzadeh M, Sajadi SM, Rostami-Vartooni A, Bagherzadeh M (2015) Green synthesis of Pd/CuO nanoparticles by *Theobroma cacao* L. seeds extract and their catalytic performance for the reduction of 4-nitrophenol and phosphine-free Heck coupling reaction under aerobic conditions. J Colloid Interface Sci 448:106–113. https://doi.org/10.1016/j.jcis.2015.02.009

Nasrollahzadeh M, Sajadi SM, Rostami-Vartooni A, Hussin SM (2016) Green synthesis of CuO nanoparticles using aqueous extract of *Thymus vulgaris* L. leaves and their catalytic performance for N-arylation of indoles and amines. J Colloid Interface Sci 466:113–119. https://doi.org/10.1016/j.jcis.2015.12.018

Neag MA, Mocan A, Echeverría J et al (2018) Berberine: botanical occurrence, traditional uses, extraction methods, and relevance in cardiovascular, metabolic, hepatic, and renal disorders. Front Pharmacol 9:557. https://doi.org/10.3389/fphar.2018.00557

Nelson DL, Cox MM (2005) Lehninger principles of biochemistry, 4th edn. W.H. Freeman, New York

O'Connell DW, Birkinshaw C, O'Dwyer TF (2008) Heavy metal adsorbents prepared from the modification of cellulose: a review. Bioresour Technol 99:6709–6724. https://doi.org/10.1016/j.biortech.2008.01.036

Ogata T, Nakano Y (2005) Mechanisms of gold recovery from aqueous solutions using a novel tannin gel adsorbent synthesized from natural condensed tannin. Water Res 39:4281–4286. https://doi.org/10.1016/j.watres.2005.06.036

Okechukwu Dominic O, Valentine Chikaodili A, Chizoba Sandra O (2020) Optimum prediction for inhibition efficiency of *Sapium ellipticum* leaf extract as corrosion inhibitor of aluminum alloy (AA3003) in hydrochloric acid solution using electrochemical impedance spectroscopy and response surface methodology. Bull Chem Soc Ethiop 34:175–191. https://doi.org/10.4314/bcse.v34i1.17

Okuda T, Yoshida T, Hatano T (2000) Correlation of oxidative transformations of hydrolyzable tannins and plant evolution. Phytochemistry 55:513–529. https://doi.org/10.1016/S0031-9422(00)00232-6

Oladoja NA, Alliu YB, Ofomaja AE, Unuabonah IE (2011) Synchronous attenuation of metal ions and colour in aqua stream using tannin–alum synergy. Desalination 271:34–40. https://doi.org/10.1016/j.desal.2010.12.008

Olasehinde T, Olaniran A, Okoh A (2017) Therapeutic potentials of microalgae in the treatment of Alzheimer's disease. Molecules 22:480. https://doi.org/10.3390/molecules22030480

Oleszek W, Hamed A (2010) Saponin-based surfactants. In: Kjellin M, Johansson I (eds) Surfactants from renewable resources. Wiley, Chichester, pp 239–249

Ownby JD, Popham HR (1990) Citrate reverses the inhibition of wheat root growth caused by aluminum. J Plant Physiol 135:588–591. https://doi.org/10.1016/S0176-1617(11)80641-3

Pangeni B, Paudyal H, Abe M et al (2012) Selective recovery of gold using some cross-linked polysaccharide gels. Green Chem 14:1917. https://doi.org/10.1039/c2gc35321k

Pangestuti R, Kim S-K (2011) Neuroprotective effects of marine algae. Mar Drugs 9:803–818. https://doi.org/10.3390/md9050803

Park J-H, Lee M, Park E (2014) Antioxidant activity of orange flesh and peel extracted with various solvents. Prev Nutr Food Sci 19:291–298. https://doi.org/10.3746/pnf.2014.19.4.291

Park T, Kim JY, Cho H et al (2017) Artificial spores: immunoprotective nanocoating of red blood cells with supramolecular ferric ion-tannic acid complex. Polymers 9:140. https://doi.org/10.3390/polym9040140

Pathak A, Dastidar MG, Sreekrishnan TR (2009) Bioleaching of heavy metals from sewage sludge: a review. J Environ Manage 90:2343–2353. https://doi.org/10.1016/j.jenvman.2008.11.005

Pelletier SW (ed) (1996) Alkaloids: chemical and biological perspectives, vol 11. Wiley, New York

Permana YN, Yulizar Y (2017) Potency of *Parkia speciosa* Hassk seed extract for green synthesis of CdO nanoparticles and its characterization. IOP Conf Ser Mater Sci Eng 188:012018. https://doi.org/10.1088/1757-899X/188/1/012018

Pietrobelli JMT, de Módenes A, Fagundes-Klen AN, Espinoza-Quiñones MR (2009) Cadmium, copper and zinc biosorption study by non-living *Egeria densa* biomass. Water Air Soil Pollut 202:385–392. https://doi.org/10.1007/s11270-009-9987-x

Pietta P-G (2000) Flavonoids as antioxidants. J Nat Prod 63:1035–1042. https://doi.org/10.1021/np9904509

Popova TN, Pinheiro de Carvalho MÂA (1998) Citrate and isocitrate in plant metabolism. Biochim Biophys Acta BBA Bioenerg 1364:307–325. https://doi.org/10.1016/S0005-2728(98)00008-5

Posmyk MM, Kontek R, Janas KM (2009) Antioxidant enzymes activity and phenolic compounds content in red cabbage seedlings exposed to copper stress. Ecotoxicol Environ Saf 72:596–602. https://doi.org/10.1016/j.ecoenv.2008.04.024

Prabha K, Rajam S, Venkatraman B (2012) The effect of aegle marmelos leaves extract on corrosion inhibition of aluminium in alkaline solution. Der Chemica Sinica 3:114–123

Punjabi K, Choudhary P, Samant L et al (2015) Biosynthesis of nanoparticles: a review. Int J Pharm Sci Rev Res 30:219–226

Qi X-L, Peng X, Huang Y-Y et al (2015) Green and efficient extraction of bioactive flavonoids from *Equisetum palustre* L. by deep eutectic solvents-based negative pressure cavitation method combined with macroporous resin enrichment. Ind Crops Prod 70:142–148. https://doi.org/10.1016/j.indcrop.2015.03.026

Rahim A, Kassim J (2008) Recent development of vegetal tannins in corrosion protection of iron and steel. Recent Pat Mater Sci 1:223–231. https://doi.org/10.2174/1874464810801030223

Rahim AA, Kassim MJ, Rocca E, Steinmetz J (2011) Mangrove (*Rhizophora apiculata*) tannins: an eco-friendly rust converter. Corros Eng Sci Technol 46:425–431. https://doi.org/10.1179/174327809X457003

Rahim MdA, Kristufek SL, Pan S et al (2019) Phenolic building blocks for the assembly of functional materials. Angew Chem Int Ed 58:1904–1927. https://doi.org/10.1002/anie.201807804

Raja PB, Sethuraman MG (2008) Natural products as corrosion inhibitor for metals in corrosive media—a review. Mater Lett 62:113–116. https://doi.org/10.1016/j.matlet.2007.04.079

Ranty B, Aldon D, Galaud J-P (2006) Plant calmodulins and calmodulin-related proteins: multifaceted relays to decode calcium signals. Plant Signal Behav 1:96–104. https://doi.org/10.4161/psb.1.3.2998

Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? Plant Sci 180:169–181. https://doi.org/10.1016/j.plantsci.2010.08.016

Ratheesh G, Tian L, Venugopal JR et al (2017) Role of medicinal plants in neurodegenerative diseases. Biomanuf Rev 2:2. https://doi.org/10.1007/s40898-017-0004-7

Ravikumar BS, Nagabhushana H, Sunitha DV et al (2014) Plant latex mediated green synthesis of $ZnAl_2O_4$:Dy^{3+} (1–9mol%) nanophosphor for white light generation. J Alloys Compd 585:561–571. https://doi.org/10.1016/j.jallcom.2013.09.080

Rellán-Álvarez R, Abadía J, Álvarez-Fernández A (2008) Formation of metal-nicotianamine complexes as affected by pH, ligand exchange with citrate and metal exchange. A study by electrospray ionization time-of-flight mass spectrometry. Rapid Commun Mass Spectrom 22:1553–1562. https://doi.org/10.1002/rcm.3523

Reyers F, Naude T (2012) Oxalate-containing plants. Veterinary toxicol veterinary toxicology: basic and clinical principles, 2ndedn. Academic Press, Amsterdam

Rice-Evans C (2004) Flavonoids and isoflavones: absorption, metabolism, and bioactivity. Free Radic Biol Med 36:827–828. https://doi.org/10.1016/j.freeradbiomed.2003.12.012

Richau K, Schat H (2009) Intraspecific variation of nickel and zinc accumulation and tolerance in the hyperaccumulator *Thlaspi caerulescens*. Plant Soil 314:253–262. https://doi.org/10.1007/s11104-008-9724-z

Richau KH, Kozhevnikova AD, Seregin IV et al (2009) Chelation by histidine inhibits the vacuolar sequestration of nickel in roots of the hyperaccumulator *Thlaspi caerulescens*. New Phytol 183:106–116. https://doi.org/10.1111/j.1469-8137.2009.02826.x

Robards K, Antolovich M (1997) Analytical chemistry of fruit bioflavonoids: a review. Analyst 122:11R–34R. https://doi.org/10.1039/a606499j

Rosaline Vimala J, Leema Rose A, Raja S (2012) A study on the phytochemical analysis and corrosion inhibition on mild steel by *Annona muricata* L. leaves extract in 1 N hydrochloric acid. Der Chemica Sinica 3:582–588

Ruttkay-Nedecky B, Nejdl L, Gumulec J et al (2013) The role of metallothionein in oxidative stress. Int J Mol Sci 14:6044–6066. https://doi.org/10.3390/ijms14036044

Sajjadi M, Nasrollahzadeh M, Mohammad Sajadi S (2017) Green synthesis of Ag/Fe_3O_4 nanocomposite using *Euphorbia peplus* Linn leaf extract and evaluation of its catalytic activity. J Colloid Interface Sci 497:1–13. https://doi.org/10.1016/j.jcis.2017.02.037

Samsonowicz M, Regulska E (2017) Spectroscopic study of molecular structure, antioxidant activity and biological effects of metal hydroxyflavonol complexes. Spectrochim Acta A Mol Biomol Spectrosc 173:757–771. https://doi.org/10.1016/j.saa.2016.10.031

Sanatkumar BS, Nayak J, Nityananda Shetty A (2012) Influence of 2-(4-chlorophenyl)-2-oxoethyl benzoate on the hydrogen evolution and corrosion inhibition of 18 Ni 250 grade weld aged maraging steel in 1.0 M sulfuric acid medium. Int J Hydrog Energy 37:9431–9442. https://doi.org/10.1016/j.ijhydene.2012.02.165

Sankar R, Manikandan P, Malarvizhi V et al (2014) Green synthesis of colloidal copper oxide nanoparticles using *Carica papaya* and its application in photocatalytic dye degradation. Spectrochim Acta A Mol Biomol Spectrosc 121:746–750. https://doi.org/10.1016/j.saa.2013.12.020

Sannomiya M, Fonseca VB, da Silva MA et al (2005) Flavonoids and antiulcerogenic activity from *Byrsonima crassa* leaves extracts. J Ethnopharmacol 97:1–6. https://doi.org/10.1016/j.jep.2004.09.053

Santos-Buelga C, Scalbert A (2000) Proanthocyanidins and tannin-like compounds—nature, occurrence, dietary intake and effects on nutrition and health. J Sci Food Agric 80:1094–1117

Saputra IS, Yulizar Y (2017) Biosynthesis and characterization of ZnO nanoparticles using the aqueous leaf extract of *Imperata cylindrica L.* IOP Conf Ser Mater Sci Eng 188:012004. https://doi.org/10.1088/1757-899X/188/1/012004

Sari IP, Yulizar Y (2017) Green synthesis of magnetite (Fe_3O_4) nanoparticles using *Graptophyllum pictum* leaf aqueous extract. IOP Conf Ser Mater Sci Eng 191:012014. https://doi.org/10.1088/1757-899X/191/1/012014

Satoh K, Sakagami H (1997) Effect of metal ions on radical intensity and cytotoxic activity of ascorbate. Anticancer Res 17:1125–1129

Schofield P, Mbugua DM, Pell AN (2001) Analysis of condensed tannins: a review. Anim Feed Sci Technol 91:21–40. https://doi.org/10.1016/S0377-8401(01)00228-0

Scotti L, Fernandes MB, Muramatsu E et al (2011) 13 C NMR spectral data and molecular descriptors to predict the antioxidant activity of flavonoids. Braz J Pharm Sci 47:241–249. https://doi.org/10.1590/S1984-82502011000200005

Seabra RM, Andrade PB, Valentão P et al (2010) Phenolic profiles of Portuguese olives. Olives and olive oil in health and disease prevention. Elsevier, Amsterdam, pp 177–186

Sedik A, Lerari D, Salci A et al (2020) Dardagan fruit extract as eco-friendly corrosion inhibitor for mild steel in 1 M HCl: electrochemical and surface morphological studies. J Taiwan Inst Chem Eng 107:189–200. https://doi.org/10.1016/j.jtice.2019.12.006

Seneviratne G, Jayasinghearachchi HS (2003) Mycelial colonization by bradyrhizobia and azorhizobia. J Biosci 28:243–247. https://doi.org/10.1007/BF02706224

Şengil İA, Özacar M (2008) Biosorption of Cu(II) from aqueous solutions by mimosa tannin gel. J Hazard Mater 157:277–285. https://doi.org/10.1016/j.jhazmat.2007.12.115

Şengil İA, Özacar M (2009) Competitive biosorption of Pb^{2+}, Cu^{2+} and Zn^{2+} ions from aqueous solutions onto valonia tannin resin. J Hazard Mater 166:1488–1494. https://doi.org/10.1016/j.jhazmat.2008.12.071

Seregin IV, Kozhevnikova AD (2020) Low-molecular-weight ligands in plants: role in metal homeostasis and hyperaccumulation. Photosynth Res. https://doi.org/10.1007/s11120-020-00768-1

Shameli K, Bin Ahmad M, Jaffar Al-Mulla EA et al (2012) Green biosynthesis of silver nanoparticles using *Callicarpa maingayi* stem bark extraction. Molecules 17:8506–8517. https://doi.org/10.3390/molecules17078506

Shankar SS, Rai A, Ahmad A, Sastry M (2004) Rapid synthesis of Au, Ag, and bimetallic Au core–Ag shell nanoparticles using Neem (*Azadirachta indica*) leaf broth. J Colloid Interface Sci 275:496–502. https://doi.org/10.1016/j.jcis.2004.03.003

Sharma SS, Schat H, Vooijs R (1998) In vitro alleviation of heavy metal-induced enzyme inhibition by proline. Phytochemistry 49:1531–1535. https://doi.org/10.1016/S0031-9422(98)00282-9

Shirmohammadli Y, Efhamisisi D, Pizzi A (2018) Tannins as a sustainable raw material for green chemistry: a review. Ind Crops Prod 126:316–332. https://doi.org/10.1016/j.indcrop.2018.10.034

Siddiqi KS, Husen A (2017) Recent advances in plant-mediated engineered gold nanoparticles and their application in biological system. J Trace Elem Med Biol 40:10–23. https://doi.org/10.1016/j.jtemb.2016.11.012

Sigamoney M, Shaik S, Govender P et al (2016) African leafy vegetables as bio-factories for silver nanoparticles: a case study on *Amaranthus dubius* C Mart. Ex Thell. South Afr J Bot 103:230–240. https://doi.org/10.1016/j.sajb.2015.08.022

Singh P, Srivastava V, Quraishi MA (2016) Novel quinoline derivatives as green corrosion inhibitors for mild steel in acidic medium: electrochemical, SEM, AFM, and XPS studies. J Mol Liq 216:164–173. https://doi.org/10.1016/j.molliq.2015.12.086

Smeriglio A, Barreca D, Bellocco E, Trombetta D (2017) Proanthocyanidins and hydrolysable tannins: occurrence, dietary intake and pharmacological effects: pharmacological aspects of tannins. Br J Pharmacol 174:1244–1262. https://doi.org/10.1111/bph.13630

Song S, Zhu L, Zhou W (2008) Simultaneous removal of phenanthrene and cadmium from contaminated soils by saponin, a plant-derived biosurfactant. Environ Pollut 156:1368–1370. https://doi.org/10.1016/j.envpol.2008.06.018

Speziali M, Orvini E (2003) Metals distribution and regionalization in the brain. Metal ions and neurodegenerative disorders. World Scientific, Singapore, pp 15–65

Stefanakis AI, Thullner M (2016) Fate of phenolic compounds in constructed wetlands treating contaminated water. In: Ansari AA, Gill SS, Gill R et al (eds) Phytoremediation. Springer International Publishing, Cham, pp 311–325

Strobel BW (2001) Influence of vegetation on low-molecular-weight carboxylic acids in soil solution—a review. Geoderma 99:169–198. https://doi.org/10.1016/S0016-7061(00)00102-6

Su D, Xie X, Dou S, Wang G (2015) CuO single crystal with exposed {001} facets—a highly efficient material for gas sensing and Li-ion battery applications. Sci Rep 4:5753. https://doi.org/10.1038/srep05753

Subha V, Ernest R, Sruthi P, Renganathan S (2015) An eco-friendly approach for synthesis of silver nanoparticles using ipomoea pes-caprae root extract and their antimicrobial properties. Asian J Pharm Clin Res 8:103

Swanson (2003) Tannins and polyphenols. Encycl Food Sci Nut 5729–5733

Swatloski RP, Spear SK, Holbrey JD, Rogers RD (2002) Dissolution of cellose with ionic liquids. J Am Chem Soc 124:4974–4975. https://doi.org/10.1021/ja025790m

Taamalli A, Arráez-Román D, Barrajón-Catalán E et al (2012) Use of advanced techniques for the extraction of phenolic compounds from Tunisian olive leaves: phenolic composition and cytotoxicity against human breast cancer cells. Food Chem Toxicol 50:1817–1825. https://doi.org/10.1016/j.fct.2012.02.090

Tang F, Zhang Q, Ren D et al (2010) Functional amino acid ionic liquids as solvent and selector in chiral extraction. J Chromatogr A 1217:4669–4674. https://doi.org/10.1016/j.chroma.2010.05.013

Tang J, He J, Liu T, Xin X (2017) Removal of heavy metals with sequential sludge washing techniques using saponin: optimization conditions, kinetics, removal effectiveness, binding intensity, mobility and mechanism. RSC Adv 7:33385–33401. https://doi.org/10.1039/C7RA04284A

Thirumurugan A, Aswitha P, Kiruthika C et al (2016) Green synthesis of platinum nanoparticles using *Azadirachta indica*—an eco-friendly approach. Mater Lett 170:175–178. https://doi.org/10.1016/j.matlet.2016.02.026

Tyśkiewicz K, Konkol M, Rój E (2018) The application of supercritical fluid extraction in phenolic compounds isolation from natural plant materials. Molecules 23:2625. https://doi.org/10.3390/molecules23102625

Umaley K, Aswar A (2015) Molecular interaction study of caffeine with metal ions in aqueous solution through internal pressure. IJCPS 4:244–250

Uttara B, Singh A, Zamboni P, Mahajan R (2009) Oxidative stress and neurodegenerative diseases: a review of upstream and downstream antioxidant therapeutic options. Curr Neuropharmacol 7:65–74. https://doi.org/10.2174/157015909787602823

Vadlapudi V (2015) Novel capping agents for nanomaterials. Eur J App Sci 7:297–301

Valko M, Jomova K, Rhodes CJ et al (2016) Redox- and non-redox-metal-induced formation of free radicals and their role in human disease. Arch Toxicol 90:1–37. https://doi.org/10.1007/s00204-015-1579-5

van Rantwijk F, Sheldon RA (2007) Biocatalysis in ionic liquids. Chem Rev 107:2757–2785. https://doi.org/10.1021/cr050946x

Vanaja M, Annadurai G (2013) Coleus aromaticus leaf extract mediated synthesis of silver nanoparticles and its bactericidal activity. Appl Nanosci 3:217–223. https://doi.org/10.1007/s13204-012-0121-9

Vellaichamy B, Periakaruppan P (2016) Silver nanoparticle-embedded RGO-nanosponge for superior catalytic activity towards 4-nitrophenol reduction. RSC Adv 6:88837–88845. https://doi.org/10.1039/C6RA19834A

Vijayaraghavan K, Mahadevan A, Sathishkumar M et al (2011) Biosynthesis of Au(0) from Au(III) via biosorption and bioreduction using brown marine alga *Turbinaria conoides*. Chem Eng J 167:223–227. https://doi.org/10.1016/j.cej.2010.12.027

Vincken J-P, Heng L, de Groot A, Gruppen H (2007) Saponins, classification and occurrence in the plant kingdom. Phytochemistry 68:275–297. https://doi.org/10.1016/j.phytochem.2006.10.008

Vomáčka P, Štengl V, Henych J, Kormunda M (2016) Shape-controlled synthesis of Sn-doped CuO nanoparticles for catalytic degradation of Rhodamine B. J Colloid Interface Sci 481:28–38. https://doi.org/10.1016/j.jcis.2016.07.026

Wang J, Chen C (2009) Biosorbents for heavy metals removal and their future. Biotechnol Adv 27:195–226. https://doi.org/10.1016/j.biotechadv.2008.11.002

Wang J, Chen C (2014) Chitosan-based biosorbents: modification and application for biosorption of heavy metals and radionuclides. Bioresour Technol 160:129–141. https://doi.org/10.1016/j.biortech.2013.12.110

Wang N, Qiu Y, Hu K et al (2021) One-step synthesis of cake-like biosorbents from plant biomass for the effective removal and recovery heavy metals: effect of plant species and roles of xanthation. Chemosphere 266:129129. https://doi.org/10.1016/j.chemosphere.2020.129129

Wang Q, Tan B, Bao H et al (2019) Evaluation of *Ficus tikoua* leaves extract as an eco-friendly corrosion inhibitor for carbon steel in HCl media. Bioelectrochemistry 128:49–55. https://doi.org/10.1016/j.bioelechem.2019.03.001

Wang Y-Q, Wang M-Y, Fu X-R et al (2015) Neuroprotective effects of ginkgetin against neuroinjury in Parkinson's disease model induced by MPTP via chelating iron. Free

Radic Res 49:1069–1080. https://doi.org/10.3109/10715762.2015.1032958

Wen J, Stacey SP, McLaughlin MJ, Kirby JK (2009) Biodegradation of rhamnolipid, EDTA and citric acid in cadmium and zinc contaminated soils. Soil Biol Biochem 41:2214–2221. https://doi.org/10.1016/j.soilbio.2009.08.006

Williams RJ, Spencer JPE, Rice-Evans C (2004) Flavonoids: antioxidants or signalling molecules? Free Radic Biol Med 36:838–849. https://doi.org/10.1016/j.freeradbiomed.2004.01.001

Wink M (2003) ALKALOIDS | properties and determination. Encyclopedia of food sciences and nutrition. Elsevier, Amsterdam, pp 126–134

Witek-Krowiak A (2012) Analysis of temperature-dependent biosorption of Cu^{2+} ions on sunflower hulls: kinetics, equilibrium and mechanism of the process. Chem Eng J 192:13–20. https://doi.org/10.1016/j.cej.2012.03.075

Won SW, Kotte P, Wei W et al (2014) Biosorbents for recovery of precious metals. Bioresour Technol 160:203–212. https://doi.org/10.1016/j.biortech.2014.01.121

Wurm F, Rietzler B, Pham T, Bechtold T (2020) Multivalent ions as reactive crosslinkers for biopolymers—a. Rev Mol 25:1840. https://doi.org/10.3390/molecules25081840

Xin Lee K, Shameli K, Miyake M et al (2016) Green synthesis of gold nanoparticles using aqueous extract of *Garcinia mangostana* fruit peels. J Nanomater 2016:1–7. https://doi.org/10.1155/2016/8489094

Yan S, Xie M, Wang Y et al (2020) Semi-synthesis of a series natural flavonoids and flavonoid glycosides from scutellarin. Tetrahedron 76:130950. https://doi.org/10.1016/j.tet.2020.130950

Yang C, Landau J, Huang M, Newmark HL (2001) Inhibition of carcinogenesis by dietary polyphenolic compounds. Annu Rev Nutr 21:381–406. https://doi.org/10.1146/annurev.nutr.21.1.381

Yang L, Stöckigt J (2010) Trends for diverse production strategies of plant medicinal alkaloids. Nat Prod Rep 27:1469. https://doi.org/10.1039/c005378c

Yang S, Wang C, Chen L, Chen S (2010) Facile dicyandiamide-mediated fabrication of well-defined CuO hollow microspheres and their catalytic application. Mater Chem Phys 120:296–301. https://doi.org/10.1016/j.matchemphys.2009.11.005

Yao L, Jiang Y, Datta N et al (2004) HPLC analyses of flavanols and phenolic acids in the fresh young shoots of tea (*Camellia sinensis*) grown in Australia. Food Chem 84:253–263. https://doi.org/10.1016/S0308-8146(03)00209-7

Yermiyahu U, Kinraide TB (2005) Binding and electrostatic attraction of trace elements to plant root surfaces. Biogeochemistry of trace elements in the rhizosphere. Elsevier, Amsterdam, pp 365–389

Yokozawa T, Chen CP, Dong E et al (1998) Study on the inhibitory effect of tannins and flavonoids against the 1,1-diphenyl-2-picrylhydrazyl radical. Biochem Pharmacol 56:213–222. https://doi.org/10.1016/S0006-2952(98)00128-2

Yulizar Y, Latifah I, Bakri R, Apriandanu DOB (2018) Plants extract mediated synthesis of copper (II) oxide nanoparticles using *Oldenlandia corymbosa* L. leaf. Bali, Indonesia, p 020097

Yurtsever M, Şengil İA (2009) Biosorption of Pb(II) ions by modified quebracho tannin resin. J Hazard Mater 163:58–64. https://doi.org/10.1016/j.jhazmat.2008.06.077

Yuryev VP, Cesàro A, Bergthaller WJ (eds) (2002) Starch and starch containing origins: structure, properties, and new technologies. Nova Science Publishers, New York

Zainal-Abidin MH, Hayyan M, Hayyan A, Jayakumar NS (2017) New horizons in the extraction of bioactive compounds using deep eutectic solvents: a review. Anal Chim Acta 979:1–23. https://doi.org/10.1016/j.aca.2017.05.012

Zhang W, Huang H, Tan F et al (2010a) Influence of EDTA washing on the species and mobility of heavy metals residual in soils. J Hazard Mater 173:369–376. https://doi.org/10.1016/j.jhazmat.2009.08.087

Zhang W, Tong L, Yuan Y et al (2010b) Influence of soil washing with a chelator on subsequent chemical immobilization of heavy metals in a contaminated soil. J Hazard Mater 178:578–587. https://doi.org/10.1016/j.jhazmat.2010.01.124

Zhang X, Li W, Yu G et al (2020) Evaluation of *Idesia polycarpa* Maxim fruits extract as a natural green corrosion inhibitor for copper in 0.5 M sulfuric acid solution. J Mol Liq 318:114080. https://doi.org/10.1016/j.molliq.2020.114080

Zhou W, Yang J, Lou L, Zhu L (2011) Solubilization properties of polycyclic aromatic hydrocarbons by saponin, a plant-derived biosurfactant. Environ Pollut 159:1198–1204. https://doi.org/10.1016/j.envpol.2011.02.001

Zin MM, Anucha CB, Bánvölgyi S (2020) Recovery of phytochemicals via electromagnetic irradiation (microwave-assisted-extraction): betalain and phenolic compounds in perspective. Foods 9:918. https://doi.org/10.3390/foods9070918

Zou J, Taylor P, Dornan J, Robinson S (2000) First crystal structure of a medicinally relevant gold protein complex: unexpected binding of [Au(PEt3)] + to histidine. Angew Chem Int 39:2931–2934

Zou Z, Qiu R, Zhang W et al (2009) The study of operating variables in soil washing with EDTA. Environ Pollut 157:229–236. https://doi.org/10.1016/j.envpol.2008.07.009

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