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Applicability of plant part extracts of Sapindus species towards corrosion inhibition and related sectors- An overview

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Abstract

This review initiative had explored the applicability of the extract isolated from various plant parts of *Sapindus (S.)* species as potential green corrosion inhibitors (GCIs). Additionally, insights on topics like plant extracts in broad, concept of corrosion inhibition by the pool of biomolecules, use of *(S.)* species plant parts as the extract to retard corrosion of metals/alloys, composition of *(S.)* species extract, extraction techniques, etc were also covered. This article would form a platform to establish the present global status of *(S.)* species towards corrosion inhibition filed and related sectors (surfactant based). The favorable functional groups featuring in the biomolecules (having maximum hydrophilic part) along with the dominant inhibitor component (saponins) present in the *(S.)* extract had assisted the effective inhibition of corrosion in metals/alloys. This behavior of the extract (having the pool of biomolecules) can be attributed to various factors like superior adsorption, firm complexation and impermeable layer development over the surface of metal/alloy. This review initiative can promote the use of *(S.)* extract in commercial scale to retard the corrosion of various metals/alloys and hence can add financial angle for the cultivators.

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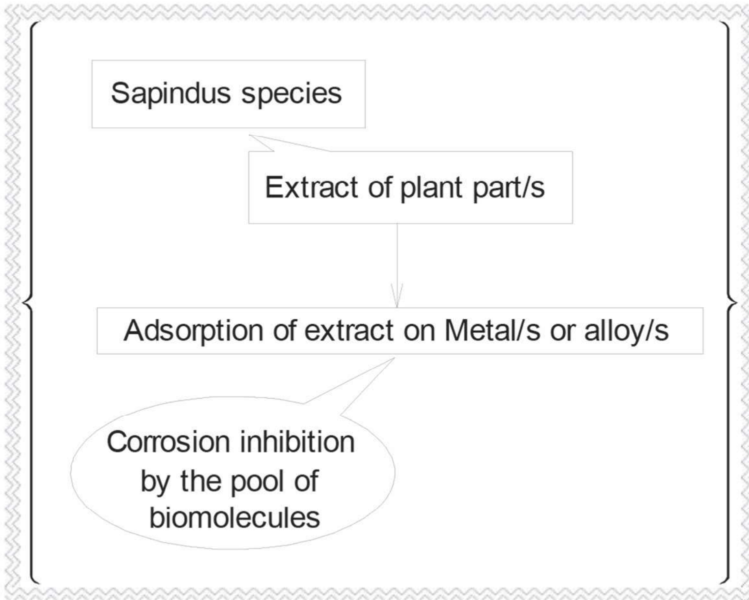
Graphical abstract.



Keywords: *Sapindus* species, Plant parts, Extraction, Biomolecules, Adsorption, Corrosion inhibition, Green corrosion inhibitors (GCIs).

1 Introduction

Sapindus (*S.*) is a genus of about 5–14 species of shrubs and small trees, being categorized under the family 'Sapindaceae' [1]. The plants variants tabulated under the genus (*S.*) were commonly termed as soapberries/soapnuts. The fruit pulp of these species was used in olden days to make soap/detergent, **Table 1**. Among the existing *(S.)* species, only a few variants like *S. mukorossi*, *S. trifoliatus* and *S. saponaria* were well explored by the global researchers for its utility as medicine, cleansing agent and in cosmetic products [2-4]. The presence of saponins in high concentration along with other biomolecules in the extract of (*S.*) species had provided high medicinal value. Hence, the species gave moderate economical benefits for its cultivators and collectors from long back [5, 6].

Table 1: Botanical details and geographical distribution data of (*S.*) species

Category	**Details**
Kingdom	Plantae, belongs to Angiosperms & Eudicots
Class	Magnoliopsida
Sub-class	Rosidae
Order	Sapindales
Family	Sapindaceae
Sub-family	Sapindoideae

Genus	*Sapindus (S.)*
In general	Soapberries/Soapnuts
Variants & native to	*(S.) trifoliatus* [India]; *(S.) saponaria* [America]; *(S.) mukorossi* [China & north-eastern India]; *(S.) delavayi* [China & India]; *(S.) detergens; (S.) emarginatus* (southern Asia); *(S.) laurifolia* [India]; *(S.) marginatus* [Florida]; *(S.) vitiensis* [America & Fiji]; *(S.) tomentosus* [China]; *(S.) oahuensis* [Hawaii]; *(S.) rarak* [south-eastern Asia]; *(S.) lippoldii; (S.) sonlaensis*
Common names	Indian soapberry, Ritha, Western soapberry, Chinese soapberry, Soapnut, Florida soapberry, Lonomea etc.
Origin of name	*Sapindus (S.)*: This generic name has derived from the popular latin words like saponis (soap) and indicus (India).

In this review segment, insights on the applicability of plant part extracts of *(S.)* species as potential GCI was provided by considering its extension to other closely related sectors. For better readability, a few sections are included such as background on the utility of *(S.)* species, note on the applicability of plant extracts, use of *(S.)* species towards corrosion inhibition-exfoliation of prior arts, composition of plant part extracts of *(S.)* species, Extraction of saponins from *(S.)* species, outline concept of corrosion inhibition by biomolecules/ phytochemicals, impact of saponins towards corrosion inhibition and future scope, and limitations and challenges.

1.1. Background on the utility of (*S.*) species

In olden days, the plant parts (as extract) of *S. mukorossi* and *S. trifoliatus* were routinely used routinely by the people as detergent to wash clothes. The fruit extracts of these plants were used to restore the brightness of ornaments made up of gold, silver, and other precious metals [7]. It was found very effective towards cleaning and bleaching of cardamoms [8], soil reclamation and phytoremediation [9], hair and cloth washing [10], folk medicinal applications, insecticidal features, tan and freckles removal from the skin [11, 12], biodiesel production [13], reforestation initiatives [14], and solubilizing features [15].

1.2. Note on the applicability of plant extracts

Plant extracts (water/solvent based) and oils obtained from various plant parts are the rich sources of useful biomolecules/phytochemicals. The impact of biomolecules was explored by numerous researchers in various sectors like therapeutics, surfactants, cosmetics, preservatives, agriculture industry, corrosion inhibition etc [16-23]. The medicinal use of plant derived biomolecules was proved in various human ailments like infections, hypertension, neuro-degeneration, cancer, diabetes, cardio-vascular diseases etc [24]. The biomolecules which facilitate to cure ailments are carbohydrates, flavonoids, steroids, tannins, alkaloids and terpenoids.

These molecules are produced in plants during the primary and secondary metabolic reactions [25, 26]. The plants extracts having higher percentage of saponins can satisfactorily replace the synthetic surfactants in numerous commercial products. This tendency can be attributed to the superior surface-active behavior of saponins having amphiphilic structure in aqueous phase. Hence, we can observe the existence of lipophilic non-polar aglycone and hydrophilic polar glycone moieties in saponins [18, 27]. The use of plant extracts in cosmetic and preservative sector had increased in recent years due to the presence of bioorigin antioxidants. These molecules are very efficient to retard oxidative stress on the skin and to protect products from the oxidative degradation [28, 29]. The plant extracts are extensively used worldwide to control phytopathogens, microorganisms, and insects. The applicability was extended later to determine the biostimulant effects, resistance induction features and herbicide effects, etc [30]. The use of plant extracts has many advantages like very low toxicity, increased resistance of plants, higher yields, superior crop quality and less dependency on synthetic fertilizers and pesticides [31]. The extracts of various plant species were explored by numerous global researchers as potential corrosion inhibitors to protect ferrous metals [32], non-ferrous metals and even some alloys [33]. For instance, *Colocasia*, *Alocasia* and *Lawsonia* species were well explored towards their corrosion inhibition behavior [34, 35]. These biobased (extracts) are established to be very effective corrosion inhibitors and are popularly termed as GCIs [36-40].

1.3. Use of *(S.)* species towards corrosion inhibition-Exfoliation of prior arts

Limited prior arts are available in the global scientific repositories regarding the use of plant part extracts of *(S.)* species as potential GCIs. However, this article is not limited only to the corrosion inhibition applicability of plant part extracts of *(S.)* species but also extended towards some of its adsorption related sectors **Table 2** and **Table 3**. To the context, 23 articles were traced by using various search terms and the work highlights were depicted chronologically for the ease of better readability. Interestingly, 12 disclosures were found to be original articles and the remaining 11 were published as review articles in various journals. It was observed that, *(S.)* species extract was used in different concentrations (50 to 4000 ppm) at varied temperatures (25 to 60^{o}C) to estimate the corrosion inhibition efficiency in the available limited attempts. The extracts of (S.) species were used as such, or along with other phytoextracts or with low concentration of specific metal ions to increase its inhibition efficiency and expand its usability across different metals/alloys in various mediums.

Table 2: Details of prior arts disclosed as original articles on the applicability of plant part extracts of (*S.*) species towards corrosion inhibition and related sectors.

Work by	Type of inhibitor, target metal and medium	Work outcome in brief	Ref.
M. Ravi *et al*., 2025	Ethanolic extract of *(S.) mukorossi* pod, Carbon steel, Saline medium.	Use of 50-400 ppm of extract was disclosed and the best efficiency (96.9%) was for 260 ppm.	[41]
E. N. Savitri *et al*., 2024	Extract combination of Lime (*Citrus aurantifolia*), Lerak {*(S.) rarak*} and Jasmine flower (*Jasminum nudiflorum*), Al, 1.0 M HCl solution.	Use of 200 ppm of extract mixture gave better corrosion inhibition efficiency than 100 ppm with 20 min of soaking duration.	[42]
F. Narciso and J. E. de Jesús, 2022	Potassium iodide (KI) and the seed extract of *(S.) Saponaria,* ASTM A335 grade P11 steel, 1.0 M HCl solution at 25°C, 45°C and 65°C.	Use of the mixture (KI and extract) was found to be effective to retard corrosion via physisorption. Thus, the strategy was recommended for static systems and not for the dynamic systems.	[43]
M. F. A. de Alencar *et al*., 2022	Extract of *(S.) saponaria*, Cu, 1.0 M HNO_3 solution.	Use of extract gave a moderate inhibitory efficiency of around 59-80% by behaving as mixed type corrosion inhibitor.	[44]
J. J. M. Praveena *et al*., 2021	Aqueous extract of *(S.) trifoliatus* and Zn^{2+}, Mild steel, Well water at RT.	Use of solution having 10 ml of extract and 50 ppm Zn^{2+} had resulted in 97% of corrosion inhibition efficiency by behaving as an anodic type inhibitor.	[45]
A. B. Shelar *et al.*, 2021	Seed powder and aqueous extract of *(S.) mukorossi* was used as biobased workability agent, Steel fiber was employed to enhance the strength and durability concrete mixture.	Use of aqueous extract was established to be more useful as the workability agent the use of the same in the powder form. The role of extract would extend to retard the corrosion of steel and hence can be a useful biobased admixture to cement.	[46]
L. Xue *et al.,* 2020	Peel extract of *(S.) mukorossi*, Q 235 steel, 1.0 M HCl solution.	Use of peel extract (ethanol driven) having nano-micro aggregates gave very good corrosion inhibition efficiency of over 90% in acidic medium.	[47]
A. Panda *et al.*, 2020	Aqueous extract of the pericarp of *(S.) mukorossi*, Metal, Alkaline medium.	Absence of S atom, maximum hydrophilic part and minimum hydrophobic part in the extract (as biobased surfactant) had favored to retard corrosion.	[48]
A. Panda *et al*., 2019	Extract of *(S.) mukorossi*, Supportive metals, coolant system.	Use of extract as a biobased surfactant in spray cooling system gave positive results along with corrosion prevention of the process supportive metal based equipments.	[49]

V. Sharma *et al.*, 2018	Aqueous extract of *(S.)* fruits (reetha), Al, 1.0 M HCl solution.	Use of aqueous fruit extract in 2000 mg/L gave very high corrosion inhibition efficiency (98%) by behaving as mixed type inhibitor.	[50]
T. V. V. Kumar *et al.*, 2010	Pericarp (outer shell) extract of *(S.) emarginatus*, Metal, Acidic/alkaline	Use of extract was found to be very effective to manufacture garnet sand through eco-friendly pathway. The anticorrosion nature of the extract had supported the durability of supportive metal based equipments.	[51]
M. J. Sanghavi *et al.*, 1996	Extracts of *(S.) trifolianus, Acacia concian* and *Trifla*, Mild steel, HCl solution.	Use of *Acacia concian* extract was found to be very effective to prevent corrosion of mild steel in acidic phases. It is followed by Trifla and least efficiency was observed for the extract of *(S.) trifolianus.*	[52]

From 1996 to 2025 (as per **Table 2**), only 12 research articles are published in 29 years having the utilization of plant part extracts of *(S.)* species towards corrosion inhibition of a few metals and related sectors. This tally of *(S.)* species centric research publications as GCIs substantiates the explorable opportunities for the researchers in immediate future.

Table 3: Details of prior arts disclosed as review articles on the applicability of plant part extracts of (*S.*) species towards corrosion inhibition and related sectors.

Work by	**Hint of sectors and materials covered in the disclosure**	**Ref.**
A. Thakur *et al.*, 2022	Use of plants extracts, gums, and oils derived from various plant species as corrosion inhibitors was elaborated. These biobased materials are very rich in biomolecules like alkaloids, lipids, phenolic acids, saponin, quercetin, terpenoids, etc having very high adsorption ability. Additionally, influential factors, mechanism of corrosion inhibition were also addressed.	[53]
S. Bilgiç, 2022	Use of various plant extracts including *(S.)* as an effective GCI of Al in acidic mediums.	[54]
M. Behari *et al.*, 2022	Use of various surfactants for the stabilization (factors & mechanisms) and pipeline mode transportation of iron ore water slurry was covered. Specifically, the impact of "saponin" a popular nonionic surfactant isolated from *(S.) laurifolia* has been discussed under surfactant and corrosion inhibition category. The disclosure had even covered the importance of minimizing corrosion-erosion of metal utilities featuring in the process.	[55]
A. Waran and P. Chandran, 2021	Use of *(S.) mukorossi*, *(S.) trifoliatus*, *(S.) laurifolia*, and *(S.) emarginatus* in various sectors like as surfactants in industry, laundry, bioremediation, biopesticide, poultry feed supplement, biodiesel, biochar, and pharmacology was highlighted. Even though the work did not cover the corrosion inhibition aspects directly but the extension of superior surfactant features of "saponin" could be extrapolated to adsorption consequences and the related corrosion inhibition possibilities.	[56]

F. Souas *et al.*, 2021	Use of additives to support the flow of heavy crude oil was primarily covered in the work. Use of *(S.) mukorossi* extract had significantly improved the rheological properties of crude oil. The extract added had behaved as an anti-clogging and anti-corrosion agent to safeguard the supportive metal utilities featuring in the process.	[57]
F. Souas *et al.*, 2020	The impact of bio-surfactant isolated from *(S.) mukorossi* and a nonionic synthetic-surfactant Brij 30 on the flow behavior of light crude oil was estimated. The viscosity and pour point of crude oil had enormously decreased due to the presence of bio-surfactant. The addition of bio-surfactant could be an ideal option, since designing the heated pipeline requires the consideration of numerous factors like pipeline expansion, number of pumping/heating stations, heat losses along the pipeline and a higher corrosion rate of the inner pipe due to the high temperature. Moreover, the extract of *(S.) mukorossi* was renowned to reduce corrosion of metal utilities as per the past ventures.	[58]
A. Thakur and A. Kumar, 2019	Use of extracts isolated from weeds as GCIs of mild steel was focused in the work. The work had comprehensively covered numerous weeds as inhibitors and hinted on the biomolecules which are responsible for the inhibition of corrosion. Even though the work did not hint on the use of *(S.)* extracts but had mentioned the role of "saponins" to prevent the corrosion of metals.	[59]
S. Jyothi *et al.*, 2019	Use of natural products as corrosion inhibition agents in variety of mediums was discussed. Under the context, use of *(S.) trifolianus* as a GCI of steel in acidic medium was highlighted.	[60]
E. Sharmin *et al.*, 2012	Use of renewable resources as anti-corrosion agents was covered in the work. Accordingly, use of *(S.) rifolianus* and other plant extracts were covered as potential GCIs to safeguard metals/alloys.	[61]
B. E. A. Rani and B. B. J. Basu, 2012	Use of GCIs to protect metals/alloys was focused in the work. The presence of biomolecules like saponin, tannin, phlobatin, anthraquinone, cardiac glycosides, flavanoid, terpene, alkaloid etc in the extract would favor to retard corrosion.	[62]
V. N. M. Devi *et al.*, 2012	The fatty acid extracted from *(S.)* seeds had exhibited good corrosion inhibition features to safeguard mild steel and copper alloys.	[63]

1.4. Composition of plant part extracts of (*S.*) species

The plant origin secondary metabolites are the rich source of biomolecules having better adsorption features and hence are used in various sectors. These biomolecules are amphiphilic in nature and the same can be attributed its superior features with regard to adsorption, emulsion, washing/foaming, etc. The extract of *(S.) mukorossi* leaves (in methanol) contains biomolecules like alkaloids, flavonoids, phenols, carbohydrates, terpenoids, and saponins. The stem part composed of flavonoids, phenolics, and polysaccharides. The fruit part has sugars, mucilage and sesquiterpene oligoglycosides with high concentration of triterpenoid saponins. The kernel part has medium chain mono-unsaturated and poly-unsaturated fatty acids, and triglycerides. Likewise, roots, flowers, and galls have a rich source of triterpenoid saponins. Interestingly, 10.1–11.5% of saponins are present in the pericarp (fruit wall) part and 56-56.5% in the drupe (mesocarp) part. Saponins are the active biomolecules which are chemically grouped under glycosides. Based on the skeletal structure, saponins can be categorized under two major types like steroids and triterpenoids. Interestingly, *(S.)* species are rich in triterpenoid saponins [6, 64-67].

1.5. Extraction of saponins from (*S.*) species

Saponins were extracted from *(S.)* species [Ex: *(S.) mukorossi*] by the use of solvents like water, ethanol, acetone, methanol etc through traditional chemical method, microwave approach, ultrasound pathway etc [68-74]. Saponins present in the pulp powder of *(S.) laurifolia* were extracted using suitable solvents (9 variants) at different temperatures (20-70^oC). Accordingly, ethanol extraction at 60^oC for 3 hr gave the maximum yield of saponins (16.3%) and the stability tests were also found satisfactory [75]. A similar result was observed in the past for the isolated saponins from (S.) *mukorossi* [76]. Many researchers around the globe had contributed towards the isolation and structural elucidation of saponins present in *(S.)* species, **Figure 1** [77-80]. A simple water extraction (for 4 hr) of *(S.) mukorossi* pericarp was reported to give saponins in good yield (30.48%) and purity (61.38%). Interestingly, purity of the same was enriched to 78.97% by fermentation strategy [81].

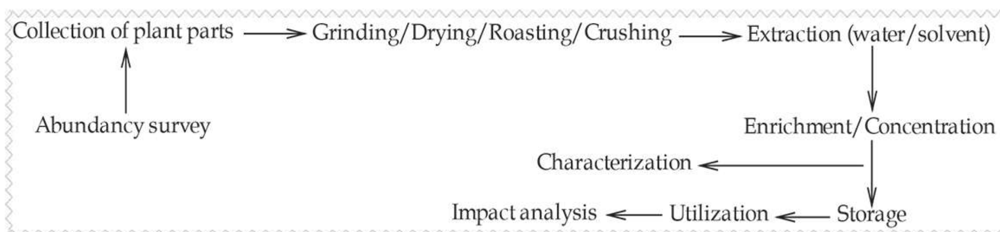


Figure 1: The common strategy followed to isolate and utilize the biomolecules of (*S.*) species.

1.6. Outline concept of corrosion inhibition by biomolecules/ phytochemicals

The reasons to go behind plant extracts as corrosion inhibitors are many like low cost, easy availability, non-toxicity, and high biodegradability. The extracts of plant parts are the rich source of biomolecules having atoms like P, S, N, O, and also the atoms having lone electron pairs (in functional groups). The presence of such a pool of atoms in plant extracts would favor adsorption consequences related to corrosion inhibition [82]. The major phytocjemicals which would support the inhibition are flavonoids, alkaloids, terpenoids, polyphenols, carbohydrates etc [83]. The efficiency of inhibition depends on the nature of multi-component based extract adsorption and its interaction on the metal surface to form a firm protective barrier to restrict the entry of aggressive H^+ or dissolved O_2. In broad, physisorption, chemisorption and retrodonation are the main mechanisms behind corrosion inhibition by plant extracts [84]. Adsorption isotherms are employed in corrosion studies to estimate how corrosion inhibitor/s interacts with metal ion (complexation) and adsorb over the metal surface (adsorption), **Figure 2** [85].

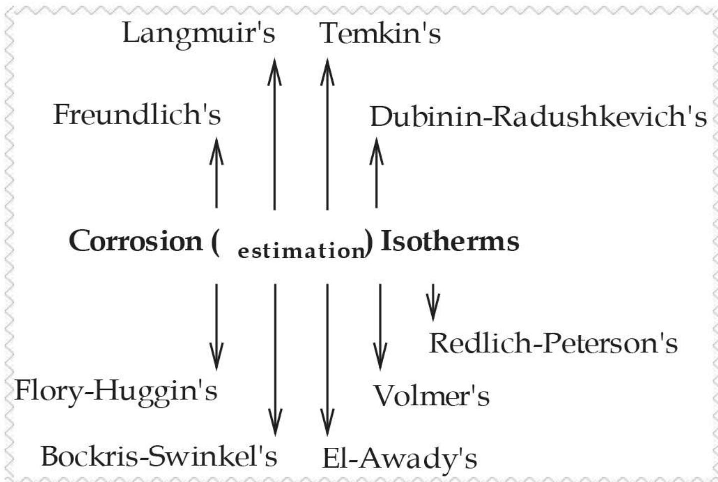


Figure 2: List of major adsorption isotherms used for corrosion studies

The inhibition of corrosion by plant extracts can be explained by the intermolecular synergistic effect imposed by the collective participation of biomolecules. Interestingly, co-adsorption occurs by cooperative or competitive corrosion inhibition at the metal surface to form one or more impermeable layers in the presence of anions. Hence on the metal surface there will be numerous types of metal-inhibitor complexes will be formed by the interaction of metal ions and biomolecules. Accordingly, Freundlich's isotherm (for heterogeneous surfaces and multi-layer adsorption) can be employed in these instances for the elaboration of the corrosion retardation processes. The mechanism of corrosion inhibition is always a complex process due to varied chemical interactions (electronic/structural/stereo specific) that occurs between the biomolecules and the metal/alloy surface. The estimation of thermodynamic aspects would assist to determine the tendency/spontaneity of the reactions involved. The Gibb's free energy of adsorption is negative, thus confirming the adsorption of biomolecules on to the metal surface is spontaneous. It the Gibb's free energy of adsorption is less negative than -20KJ/mol then the process is physisorption. Likewise, if it is more negative than -40KJ/mol then the process is chemisorption [86]. More importantly, the estimation of routine adsorption parameters like equilibrium constant and enthalpy has no significance in plant extract based corrosion inhibition module [87-90].

1.7. Impact of saponins towards corrosion inhibition and future scope

It is a well known fact that, biobased saponins are good corrosion inhibiting agents. Since, it has more molecules/groups with high polarity and electron rich areas. The effectiveness of saponins increases with concentration (0.5 g/L to 10 g/L), but will decrease gradually with increase in temperature [91-94]. Factually, saponins and other biomolecules present in the extract will collectively contribute to corrosion inhibition (synergistic corrosion inhibition). It was observed that, oxygen atoms/triple bonds/aromatic rings existing in saponins and other biomolecules would support electron donation to the cation species to have superior adsorption over the metal/alloy surface to form the firm impermeable layer/coating, **Figure 3**. Saponins can act as mixed-type inhibitors by affecting both anodic (metal dissolution) and cathodic (reduction) reactions of the corrosion phenomenon [95-97]. Meanwhile, the higher concentration of saponins present in the *(S.)* extract will have their own superior impact on inhibition but it is not the alone contender to induce the intended inhibition. Saponin rich plant extracts had exhibited high efficiency (up to 98%) to prevent the corrosion of mild steel and other metals/alloys in acidic/saline mediums by obeying Langmuir isotherm in most instances [98]. There are other factors like temperature, corrosive environment, plant extract composition etc would contribute for the overall inhibition efficiency. The molecular modeling and simulations studies had indicated that, saponins have very high affinity for the sandstone rocks/metal/alloy surface with strong adsorption energies [99, 100].

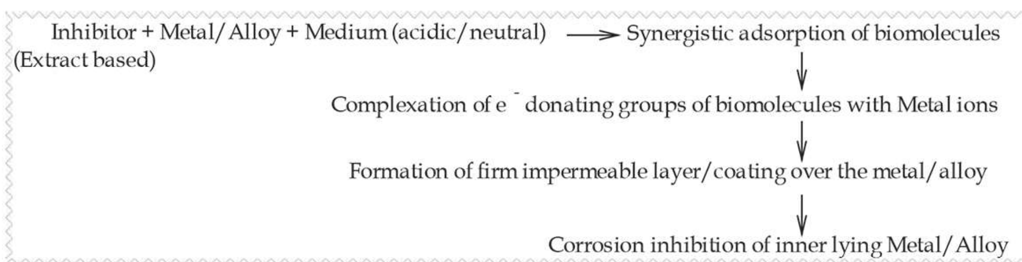


Figure 3. Inhibition of corrosion in metals/alloys by saponins and other biomolecules present in the plant part extract of *(S.)* species.

Different types of saponins are present in various parts of *(S.)* species (fruits, roots and galls) in varied concentrations. For instance, the fruit part of (S.) mukorossi contains a high concentration of saponins (six saponin variants), and the pericarp part has 10.1% of saponins. Similarly, *(S.) rarak* extract has 7.5% of saponins and *(S.) saponaria* extract has 12% of saponins. More importantly, saponins are present in all parts of the *(S.) species* and are significantly rich in fruits [2, 6, 101-103].

The plant part extracts of *(S.)* species are a promising GCI to safeguard metals/alloys in different mediums. It provides high efficiency (upto 98%), low cost, and even enough abundance for large-scale industrial applications in the future. The phytochemicals present in the extract with saponins in high concentration have supported the formation of a firm impermeable layer over the metal/alloy to retard corrosion in various ventures. With regard to the toxicity and environmental concerns associated with routine synthetic inhibitors, the plant part extracts of *(S.)* species could be an effective and feasible non-toxic and eco-friendly approach to prevent corrosion of metals/ alloys. These aspects would extend its utility still more in the sectors like oil/ gas industries, synergistic mixtures, and eco-friendly coatings.

1.8. Limitations and challenges

The major limitations and challenges behind the use of plant part extracts of *(S.)* species for corrosion inhibition are many. A few major ones are, varied composition of the extracts, variation in performance (consistency), sensitive to temperature, less effectiveness in drastic industrial scenarios, process scalability, standardization of the executable methods, low shelf-life, need for synergistic formulations (impact of added cations), compatibility issues, inhibitor dosage control, logistic issues, overall process cost, etc. In order to validate all these aspects collectively, more research should happen and hence the same would become the future scope as well.

Conclusions

This review article was primarily focused to provide insights on the anti-corrosion and related sector applicability of plant part extracts of *(S.)* species. Accordingly, 23 scientific communications were shortlisted with 12 original research articles and 11 review articles. Every disclosure was carefully examined and the outcomes were depicted in the review flow. Additionally, supportive details related to plant extracts, composition, extraction techniques, synergistic contribution of biomolecules towards corrosion inhibition, impact of saponins as surfactant for superior surface adsorption, etc. were provided with suitable references. With these collectives, this review article would certainly narrate the present status of *(S.)* species in corrosion inhibition and related sectors. This can be a useful resource for the researchers to explore more on the commercialization of *(S.)* species based technological ventures. The biomolecules of *(S.)* species can be used in different forms for various adsorption related applications, since it has proven surfactant features. The available original research articles focusing primarily on the corrosion inhibition by *(S.)* species are very limited. This aspect naturally opens up some explorable options to use the extracts of *(S.)* species towards adsorption driven fields. Furthermore, visionary research around the species can support the cultivators and collectors with financial benefits under sustainable module.

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Author contributions

Sanjay; had collected the prior arts, done the analysis, set the manuscript flow, and wrote the entire manuscript as per the journal protocol. *Shridhara*; had assisted to shortlist prior arts and correction of final manuscript.

Conflict of interest

I declare that there is no competing financial interest of any kind is associated with this review segment.

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