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Review Article

Perspectives in Biomonitoring and Pharmacological Aspects of *Parmelia sulcata* Taylor

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ABSTRACT

Over the past few decades, the rise in anthropogenic activities has led to environmental pollution. Heavy metals and metalloids like lead, arsenic, cadmium, mercury and aluminium are major pollutants hampering the harmony of the ecosystem. Biomonitoring describes various techniques and approaches for studying biological responses to pollution. The use of lichens in pollution monitoring proved to be an efficient method to curtail it. Representing a complex life form, lichens exist in a symbiotic association connecting algae and fungus. These biosensors are not only used to monitor environmental pollutants but have also been used medicinally since time immemorial. Lichens from Parmelia emerge as a valuable tool for monitoring pollution due to their unique capacity to accumulate heavy metals. *Parmelia sulcata* Taylor commonly known as shield lichen inhabited on trees, rocks and even on walls and is well distributed throughout the world from cold to temperate regions of the Northern and Southern hemispheres. For centuries, *Parmelia sulcata* has been used in traditional medicine to cure cranial disorders and also rubbed on the gums of teething babies to alleviate discomfort. It has been found that this lichen constitutes distinctive chemical constituents such as salazinic acid, atranorin, volatile oils, etc. contributing towards the anticancer, antioxidant, anti-microbial, anti-fungal and mosquitocidal potential. The prime objective of this current manuscript is to discuss the biomonitoring and pharmacological potential of *Parmelia sulcata* Taylor.

Keywords: Air pollution, Biomonitoring, *Parmelia sulcata*, Pollution, Lichen.

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INTRODUCTION

At the onset of civilization, human beings have been relying upon natural resources to fulfill their basic requirements of sustaining life viz. food, clothing and shelter.[1] It has been found that plants, animals and microorganisms exist in a close relationship and build the foundations of the ecosystem. Lichens have shown their existence in a symbiotic association, established as composite organisms comprised of algae or cyanobacteria hosted by fungi.[2] The term 'lichen' is derived from the Ancient Greek word 'leikhen', meaning 'which eats around itself',[3] and is also used in the context of 'warts'.[4] Another Greek word 'leprous' has been used in correlation with lichens recommending the utilization of lichens in alleviating skin diseases due to their peeling skin appearance.[5] They have the unique ability to adapt to terrestrial environments and constitute 6-7% of the Earth's land surface.[6] Various ancient texts revealed the extraordinary uses of lichens. In the Ancient Egyptian period, fragrant lichens were one of the major ingredients used in the process of mummification of dead bodies.[7] Lichen-derived natural colorants were extensively used in European countries for dyeing purposes during the Middle Ages.[8] The traditional Chinese system of medicine also documented a plethora of uses of lichens in dyeing, medicine, food, etc.[9] In Atharvaveda (1500 B.C.), An Ancient Indian text, different names like 'Shila Pushp' or 'Shailaya' (rock flower) have been used in the context of lichens and they have been employed by Ayurvedic practitioners in treating various diseases.[10] Some examples of medicinally established lichens used in ancient times are *Umbilicaria esculenta*,[11] *Lobaria pulmonaria*,[12] *Cetraria islandica*,[13] *Usnea longissimi*,[14] *Parmelia saxatilis*,[15] *Parmotrema reticulatum*.[16] Apart from medicinal uses, lichens have also been consumed as food due to the presence of valuable nutrients in them, the most common examples include *Dermatocarpon miniatum*,[17] *Everniastrum cirrhatum*,[18] *Evernia prunastri*,[19] *Flavocetraria nivalis*.[20] Lichens also serve as excellent indicators of global environmental change as they are sensitive to fluctuations in temperature, air pollution and water availability.[21] Lichens belonging to Genus Parmelia contain a reservoir of complex secondary metabolites capable of eliciting diverse pharmacological activities. Atranorin, salazinic acid are among the major chemical constituents present in

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Parmelia asiatica, P. cetrata, P. encryptata, P. nimandairana, P. somlesciens. Parmelia lichens have been tested involving different pharmacological models and reported to be antioxidant (*P. pertusa, P. perlata*), anti-cancer (*P. omphalodes, P. subrudecta*), anti-microbial (*P. arseneana, P. caperata*) etc.,[22] Apart from diverse pharmacological potential, lichens of this genus have the potential to serve as biomonitors. In the existing review, attempts have been made to describe the lichen *Parmelia sulcata* belonging to the Parmeliaceae family and to give insights into its biomonitoring ethnobotanical, chemical and pharmacological potential.

MATERIALS AND METHODS

Scientific databases like PubMed, Scopus, Google Scholar and PubChem were thoroughly explored to compile this review. The keywords used for the literature survey include "*Parmelia sulcata*", "lichens", "biomonitoring", "biosensor", "monitoring pollution", "shield lichen", "Parmelia pharmacology" etc.

Taxonomical classification[23]

Kingdom	Fungi
Division	Ascomycota
Class	Lecanoromycetes
Order	Lecanorales
Family	Parmeliaceae
Genus	*Parmelia*
Species	*sulcata*

Habitat

Parmelia sulcata Taylor, known as shield lichen[24] commonly found among trees and rocks distributed throughout the world from cold to temperate regions of the Northern and Southern hemispheres.

It is widespread from coastal regions to bare mountain summits.[25] In India, it is found in areas of Garhwal Himalayas, Sikkim, Jammu and Kashmir and Himachal Pradesh.[26]

Botanical Description

Saxicolous or corticolous loosely appressed overlapping thallus is orbicular, 5-20 cm diameter having sublinear-elongate, branched 1-5 mm lobes. A network of sharp ridges and depressions on lobes give this lichen a hammered-like appearance. The upper surface is often pale greenish-grey having wrinkled-faveolate, pseudocyphellae along which soralia. The lower surface is generally black, encompassing root-like structures known as rhizines which are simple to squarrosely branched, isidia are generally lacking and apothecia occasionally have red-brown to dark brown.[27-30]

Identification

Spot test

The medulla and soredia of lichen react positively with Potassium hydroxide (K) changing to orange-red and also react with para-Phenlenediamene (Pd) to turn to orange color. It does not produce fluorescence when observed under UV light.[30,31]

Ethnobotanical Uses

Lichens have been employed as an ailment in the traditional system of medicines since time immemorial.[6] In the 15th century with the outcome of 'The Doctrine of Signatures', it has been stated that plants reveal their medicinal properties via gross morphology. Lichen, *P. sulcata* is convoluted like a human brain and was used to treat several mental and cranial disorders.[32,33] It is also believed that *P. sulcata*, a saxicolous foliose lichen might be the species whose medicinal properties have been described by Pedanius Dioscorides in the first century.[34] Traditionally, it has been used by Metis people (Alberta, Canada) as a paste to be applied on the gums of teething babies to alleviate discomfort while the Saanich community (British Columbia) probably used this lichen for birth control.[35]

Biomonitoring Tool

Over a few decades, lichens have been explored as biomonitors all over the world in environment quality assessment for industrial commodities like fertilizer manufacturing plants,[36] iron and steel industries,[37] thermal and coal-fired power plants,[38] oil extraction,[39] petrochemical industry,[40] zinc and iron foundries,[41] radioactive material,[42] etc. Lichens are sensitive to industrial effluents and, hence are promising indicators for monitoring air pollution and atmospheric deposition of various air pollutants viz. PAH, POP.[43,44] Particles of elements like iron, aluminium and titanium are accumulated in lichen thallus altering the morphology of lichens. Most lichen species vary in their ion uptake capacity and efficiency of particulate trapping of its surface morphology. Therefore, the correct identification of lichen is used for biomonitoring and predicts the desirability of collecting similar species for analysis from sampling sites.[45] They, generally regarded as biosensors[46] have an inherent ability to accumulate nutrients from the surrounding environment in which they live[47] and can be employed as bioindicators by mapping species in a particular site or via individual sampling and measuring pollutants accumulated in the thallus. They can also be transplanted to contaminated areas from uncontaminated areas and then analyzed for their morphology as well as bioaccumulation of toxins.[48] Lichens viz. *Anaptychia ciliaris, Lobaria pulmonaria, Ramalina duriaei* are indicative of a polluting environment. Similarly, lichens of the genus Parmelia also proved to be potential biosensors like *P. sulcata, P. caperata* and *P. rudecta*[49,50] and have the unique ability to bioaccumulate several metal ions from their surroundings via various mechanisms, including ion exchange,[51] particulate trapping,[52] intracellular accumulation of metals etc.[53] thereby serving as a promising tool in biomonitoring research. Elements like iron, aluminum, titanium, chromium and uranium can be embedded in the thallus portion of lichen which might bring morphological changes in them. Degradation of photosynthetic pigments, ultrastructural, morphological and physiological changes and an increase in membrane permeability are the consequences of a polluted environment exhibited by lichens as illustrated in Figure 1.[45] *Parmelia sulcata* is sensitive to several pollutants like sulfur dioxide,[54] oxides of nitrogen,[55] fluorides,[56] photochemical toxins,[57] heavy metals.[58]

In a national monitoring survey covering around 32,500 km^2 of the geographical land area of The Netherlands, *P. sulcata* was employed as a bioindicator for detecting trace-element air pollution. The samples were analyzed via neutron activation analysis using INAA. The detection of several elements in epiphytic lichens gave insights into the potential uses of *Parmelia sulcata* as a biomonitor.[59]

INAA and RXRFA methods are two major techniques used to detect pollutants in the atmosphere. In a study by Musilek and his co-worker's results indicated the disappearance of lichens from the majority of polluted sites and proved the effectiveness of RXRFA and INAA methods in biomonitoring air pollution.[60]

In an environmental elemental availability study of *P. sulcata*, samples that were transplanted from non-polluted sites to polluted areas near fuel and coal-powered power plants found a high accumulation of heavy metals in lichen thalli.[61]

In a research study by Freitas *et al.*, an atmospheric deposition study involving an oil power station in Portugal, was carried out using transplanted epiphytic lichen *P. sulcata and* some emission sources (sea spray, mercury contamination in soil sample) were successfully determined by INAA and PIXE methods.[62]

According to Bennett, the total thickness of thallus and algal layer and algal layer ratio in *P. sulcata* specimens collected from 16 different polluted localities and found a significant decline in algal layer ratio and thickness of thallus, attributed to air pollution.[63]

A survey concerning activation analysis of *Parmelia sulcata,* collected from oak tree bark has been conducted by *P. sulcata* transplants were exposed to different influx systems viz. Vertical influx (Vi), Horizontal influx (Hi) and Free influx (Fi) and the elemental contents were measured by INAA and PIXE. It was found that the precipitation volumes and total element deposition showed a positive correlation for the horizontal influx and free influx systems and no prominent correlations were recorded concerning the vertical influx system.[64]

In a study by Sujetoviene, contents of nitrogen, carbon and sulphur were determined in *Physcia tenella* and *Parmelia sulcata* alongside the Kaunas-Vilnius highway, Central Lithuania to monitor the extent of traffic pollution and a prominent relation between excessive nitrogen dioxide levels and nitrogen accumulation was observed in concerned lichen thalli.[65]

Heavy metal pollution in areas of Nis, a Southeastern city in Serbia has been determined by ICP-OES involving *Parmelia sulcata* as a bioindicator and the results showed the extraordinary tendency of accumulating Mn, Ni, Ti and Fe by *P. sulcata*.[66]

P. sulcata also served as an indicator of pollution in urban environments. In a study of monitoring air pollution in the city of Pskov (Russia) carried out using *P. sulcata* results showed changes in the morphology of selected lichen. In particular necrosis, size reduction in thalli, high soredia formation and colour changes in thalli depicted the polluting urban environment.[67] The reports representing the potential biomonitoring applications of this lichen have been indicated in Table 1.

Pharmacological Potential

Apart from pollution monitoring, shield lichen has diverse applicability in various disciplines like ethnobotany, pharmacology and chemistry as indicated in Figure 2. Recently various researchers have tested this lichen for its anti-cancer, anti-microbial, antioxidant, anti-fungal and mosquitocidal potential and found promising results. The detailed pharmacological potential of *P. sulcata* has been summarised in Table 2.

Anti-cancer

In vitro, anti-cancer potential of methanolic extracts of shield lichen using several cell lines viz. A549, PC3, Hep3B and C6 cells were evaluated. These authors concluded that ethanol extract of *P. sulcata* induced cell death (apoptosis) via DNA damage in several cancer cell lines A549, PC3, Hep3B and C6 having 98.5 μg/mL, 87.3 μg/mL, 47.3 μg/mL, 64.7 μg/mL IC_{50} values respectively.[68]

Ari *et al.*, reported several volatile components viz. Methyl 2,4-dihydroxy-3,6-dimethylbenzoate (1), 3,7,11,15-Tetramethyl-2-hexadecen-1-ol (2), n-Hexadecanoic acid (3), Decalactone (4), 9-Octadecynoic acid (5), Dodecanamide (6), Pentadecane (7), 9-Octadecenal (8), Methyl isoheptadecanoate (9), 2-Methylnonadecane (10), Farnesane (11), 2-Nonadecanone (12), 1-Acetoxynonadecane (13), Eicosane (14), Hexyl 2-phenylethyl ester-succinic acid (15), 1-Heneicosanol (16), (E,E)-3,7,11-trimethyl-2,6-dodecadien-1-ol (17), Ethyl icosanoate (18), Allyl octadecyl oxalate (19), 1-Docosanol acetate (20), Squalene (21), 2-Hexyl-1-octanol (22), 2-Methyloctadecane (23), Heneicosane (24) from *P. sulcata* as confirmed by GCXGC-TOF/MS system. Results indicated that the methanolic extract of lichen inhibited the growth in a dose-dependent manner (100 μg/mL) and induced apoptosis and also showed genotoxicity at dose >125 μg/mL when tested against in MCF-7, MDA-MB-231 cell lines.[69]

Table 1: The table illustrates the biomonitoring potential of *Parmelia sulcata* Taylor.

Study conducted	Country	Site	Methodology adopted	Inference	References
Trace-element air pollution monitoring survey.	Netherlands	Area covered 32500 km^2.	INAA	The elemental concentration patterns were obtained.	[59]
Monitoring air pollution.	Czech Republic	Area covered 40000 km^2.	RXRFA and INAA	The disappearance of lichens from polluted areas as assessed by RXRFA, INAA.	[60]
Environmental elemental availability.	Portugal	6 sampling sites.	INAA, PIXE	*P. sulcata* accumulated heavy metals.	[61]
Atmospheric deposition studies.	Portugal	47 sampling stations.	INAA, PIXE	Emission sources were identified.	[62]
Monitoring air pollution.	USA	16 sampling sites.	Determination of total thallus and algal layer thickness.	A decline in algal layer ratio and thickness of thallus along with the algal layer of lichen in polluted areas.	[63]
Air pollution.	Portugal	Polluted area.	INAA, PIXE	Transplant positioning systems may have effects on element-specific net accumulation.	[64]
Road traffic pollution.	Central Lithuania	12 sampling plots.	Spectrophotometer, nitrogen sulphur analyzer	A significant relation between NO_2 levels and nitrogen accumulation was reported in lichen thalli.	[65]
Heavy metal pollution.	Southeastern Serbia	Polluted cities-Cerje, Donje Vlase.	ICP-OES	Lichen showed a tendency to accumulate Fe, Mn, Ni and Ti.	[66]
Urban environment monitoring.	Pskov, Russia	9 green areas under anthropogenic pressure located in 5 districts of Pskov city.	Evaluation of morphological parameters of the lichen's thalli.	Changes in the lichen morphology depicted a polluting environment.	[67]

Ps-AgNPs were synthesized from the phenolic extract of *Parmelia sulcata* and tested against MCF-7 and NIH-3T3. Western blotting was employed to determine the cytotoxicity profile which confirmed the selective induction of apoptosis of silver nanoparticles in MCF-7.[70]

In a study conducted by Studzinska-Sroka *et al.*, lipophilic extracts of several lichen species viz. shield lichen (*Parmelia sulcata*), *Cladonia uncialis, Evernia prunastri* were tested against GBM cell lines. The acetone extracts of *P. sulcata* contain about 23.05% of depsidone lichen metabolite (salazinic acid) as confirmed by HPLC and evaluated against A-172, T98G cell lines. Results showed that salazinic acid decreases cell viability at 100 μM concentration and *P. sulcata* extract showed activity at 50 μg/mL and 100 μg/mL concentration in both cell lines, explaining its potential in the therapeutics of glioblastoma multiforme (CNS-associated tumors).[71]

Anti-microbial

The petroleum ether, acetone, chloroform, diethyl ether and methanol extracts along with salazinic acid were investigated for their antimicrobial effects against several bacteria including *Bacillus cereus, B. subtilis, Aeromonas hydrophila, Proteus vulgaris, Streptococcus faecalis, Staphylococcus aureus, Penicillium notatum, Aspergillus niger, Candida glabrata, Candida albicans, Yersinia enterocolitica, Listeria monocytogenes* and *Aspergillus fumigatus.* Except for petroleum ether extract, all other extracts showed antimicrobial activity at different Minimum Inhibitory

Table 2: The table illustrates the pharmacological status of *P. sulcata* Taylor.

Extract	Constituents	Activity	Model	References
Methanol	Salazinic acid	Cytotoxic	A549, PC3, Hep3B, C6 cell lines.	[68]
Methanol	Volatile oils	Anti-cancer	MCF-7, MDA-MB-231.	[69]
Silver nanoparticles	Phenolics	Cancer treatment	MCF-7, NIH-3T3.	[70]
Acetone	Phenolics	Anti-cancer	A-172, T98G cell lines.	[71]
Acetone, chloroform, diethyl ether, methanol.	Salazinic acid, atranorin	Anti-microbial	Disc diffusion method.	[72]
Acetone, Methanol, aqueous.	Salazinic acid, atranorin	Anti-microbial	Disc diffusion method.	[73]
Methanolic	Flavonoids, phenolics	Anti-microbial	Microdilution method.	[74]
Ethylacetate	7-hydroxy-3-(2-methylbut-3-en2-yl)-chromen-2-one.	Anti-microbial	Microdilution method.	[75]
Acetone, methanol, chloroform.	Salazinic acid	Anti-fungal	Micro broth dilution method.	[76]
Methanolic	Flavonoids, phenolics	Antioxidant	DPPH radical scavenging.	[74]
Acetone, methanol, water.	Flavonoids, phenolics	Antioxidant	DPPH radical scavenging, ferric reducing power capacity, superoxide anion scavenging activity.	[68]
Gold nanoparticles.	Salazinic acid	Mosquitocidal effect	Bioassay	[78]

Concentration (MIC) values. The two major components of the extracts were identified as salazinic acid (25) and atranorin (26) as confirmed by infra-red spectroscopy.[72]

The antibacterial effects of acetone, methanol and aqueous extracts of *Parmelia sulcata* were also investigated. Rankovic *et al.*, employed the disk diffusion method to determine the zone of inhibition of extracts against *Bacillus mycoides, Bacillus subtilis, Staphylococcus aureus, Enterobacter cloaceae, Escherichia coli, Klebsiella pneumoniae, Aspergillus flavus, A. fumigatus, Botrytis cinerea, Candida albicans, Fusarium oxysporum, Mucor mucedo, Paecilomyces variotii, Penicillium purpurescens, P. verrucosum, Saccharomyces cerevisiae and Trichoderma harsianum.* The methanol and acetone extracts of shield lichen showed prominent inhibitory activity against all tested microorganisms except *Staphylococcus aureus.* The acetone extract reported the largest zones of inhibition (25 mm) in the case of *B. subtilis* and *E. coli* (24 mm). The aqueous extract of *P. sulcata* was inactive for tested microorganisms.[73]

In another study, methanolic extract of lichens *Parmelia sulcata, Hypogymnia physodes* and *Cladonia foliacea* was evaluated via a microdilution method involving several microorganisms. The minimum inhibitory concentrations and minimum microbicidal concentrations were calculated for 29 selected microorganisms (4 yeast species, 10 filamentous fungi, 15 bacterial strains) and were found to range from 9.8×10^{-3} mg/mL to 40.00 mg/mL. The results revealed the increasing order of antibacterial activity as *Hypogymnia physodes>Cladonia foliacea> Parmelia sulcata*.[74]

In a study by Gandhi *et al.*, the ethyl acetate fraction of *P. sulcata* was evaluated against different bacterial (*Klebsiella pneumoniae, Escherichia coli, Pseudomonas aeruginosa, Bacillus subtilis*) and fungal strains (*Aspergillus fumigatus, Candida albicans*) involving microdilution method. It is reported that flavonoids and phenolics were responsible for the antibacterial, antifungal and antioxidant activities of lichen. The compound identified as 7-hydroxy-3-(2-methylbut-3-en2-yl)-chrome-2-one may contribute to antibacterial activities.[75]

Sariozlu and his co-workers investigated the anti-fungal potential of several lichen species including *P. sulcata* against five pathogenic fungal strains viz. *Fusarium solani, Fusarium moniliforme, Aspergillus parasiticus, Aspergillus fumigatus* and *Alternaria brassicicola*. The results revealed the antifungal potential of acetone, methanol and chloroform extracts of *P. sulcata* having a minimum inhibitory concentration ranging between 156.25 to 1250 µg/mL.[76]

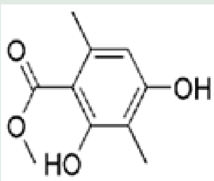
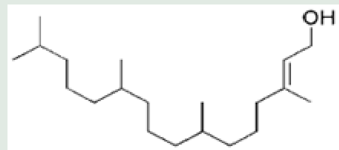
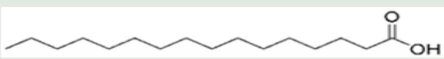
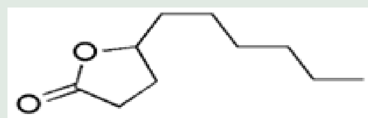
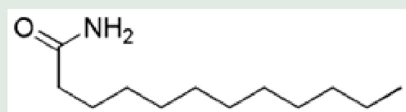
Antioxidant

Mitrovic *et al.*, reported the anti-oxidant potential of several lichen species viz. *Parmelia sulcata, Hypogymnia physodes, Evernia prunastri, Cladonia foliacea* and *Flavoparmelia caperata*, using DPPH radicals scavenging assay. The highest flavonoid content and the extract's total phenolic content, total flavonoid content and antioxidant capacity were determined and reported as 88.25±1.02, 44.43±1.22, 584.22±1.28 respectively.[74]

Several extracts of *Parmelia sulcata* were investigated for in vitro antioxidant potential. Total phenolic and flavonoid content were also determined and the results revealed that the aqueous extract of lichen *P. sulcata* demonstrated the superoxide anion scavenging activity (12.74%). The total flavonoid content of acetone, methanol and water extract was found to be 38.2±1.27, 25.1±1.11 and 9.6±1.19.[77]

Mosquitocidal

AuNPs synthesized from the aqueous extract of *Parmelia sulcata* were evaluated for mosquitocidal activity against *Anopheles stephensi, Anopheles aegypti.* AuNPs exhibited promising mosquitocidal activity when compared with *P. sulcata* extract and were found to be toxic against mosquito pupae, egg-hatching larvae and adults.[78]

 Methyl 2,4-dihydroxy-3,6-Dimethylbenzoate **(1)** PubChem CID-78435	 3,7,11,15-Tetramethyl-2-hexadecen-1-ol **(2)** PubChem CID-5366244
 n-Hexadecanoic acid (3) PubChem CID-985	 Decalactone (4) PubChem CID-12813
 9-Octadecynoic acid (5) PubChem CID-68167	 Dodecanamide (6) PubChem CID-14256
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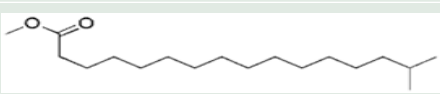
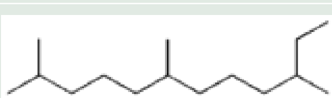
 Methyl isoheptadecanoate (9) PubChem CID-522345	 2-Methylnonadecane (10) PubChem CID-137081
 Farnesane (11) PubChem CID-19773	 2-Nonadecanone (12) PubChem CID-69423

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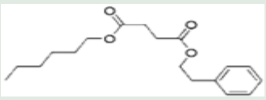 Succinic acid, hexyl 2-phenylethyl ester (15) PubChem CID- 91703188	 1-Heneicosanol (16) PubChem CID-85014
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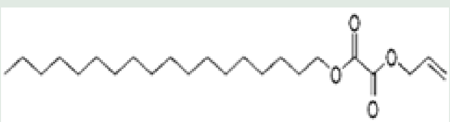
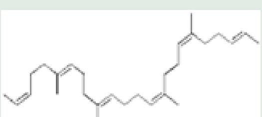
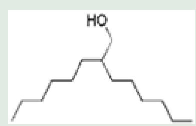
 Allyl octadecyl oxalate (19) PubChem CID- 6420237	 1-Docosanol acetate (20) PubChem CID-69969
 Squalene (21) PubChem CID- 638072	 2-Hexyl-1-octanol (22) PubChem CID-545551
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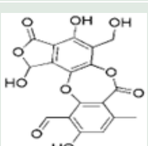
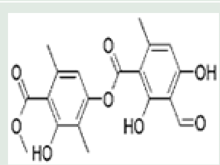
 Salazinic acid (25) PubChem CID- 5320418	 Atranorin (26) PubChem CID- 68066

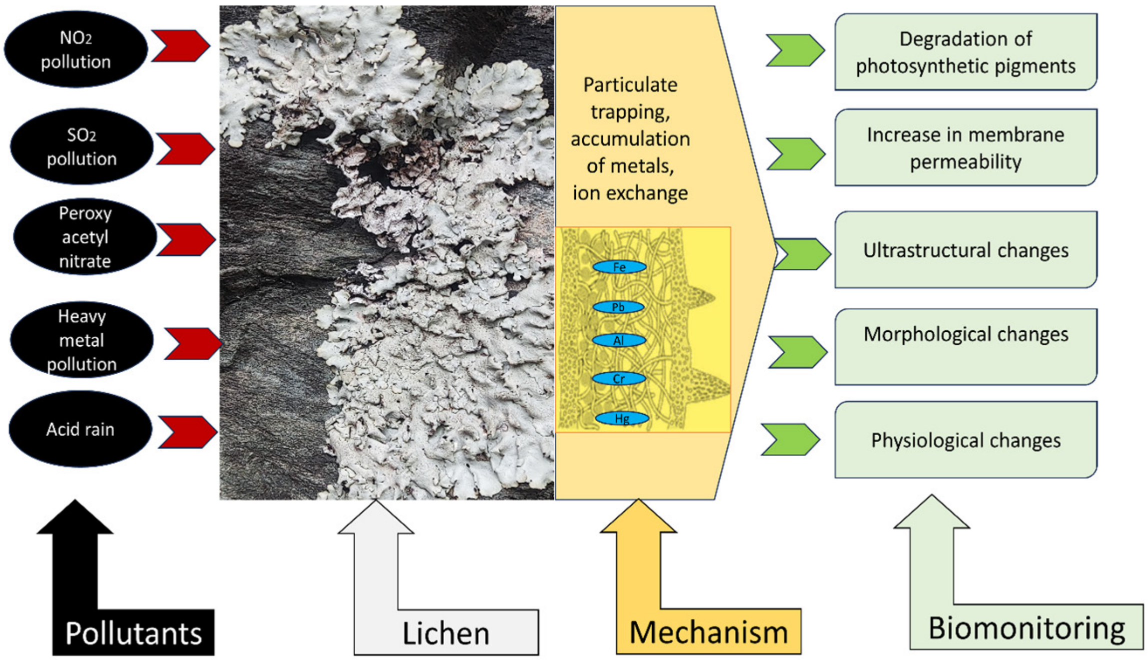


Figure 1: Biomonitoring potential of lichen.

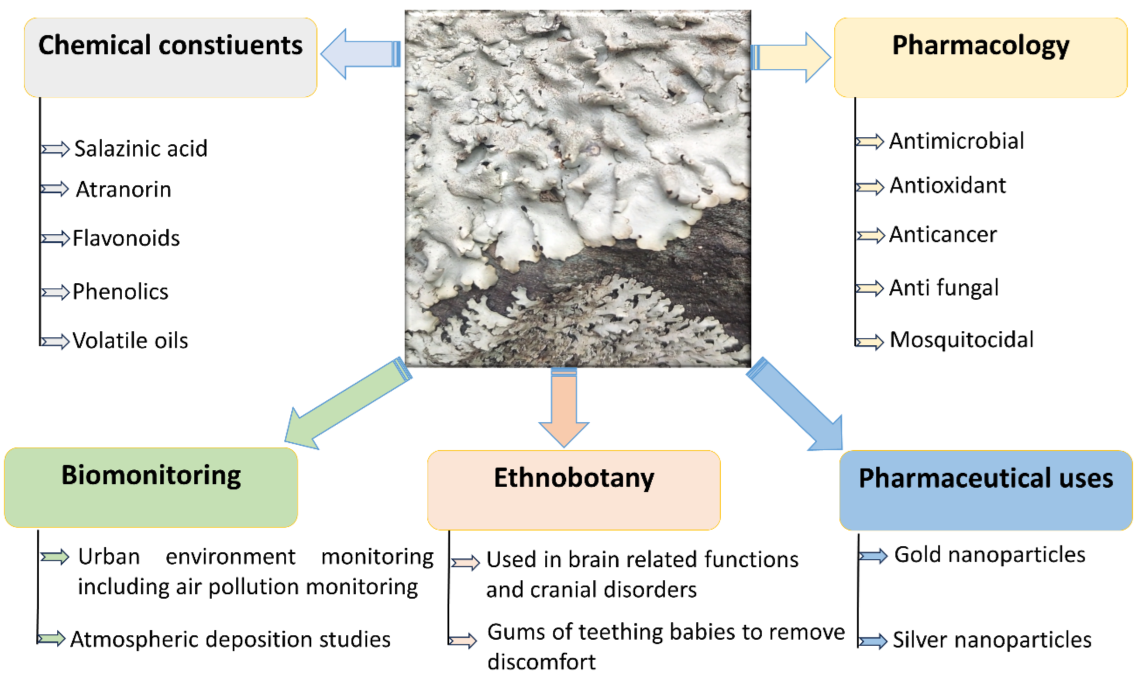


Figure 2: Potential applications of *Parmelia sulcata* Taylor.

Other Uses

P. sulcata is also known as shield lichen,[24] hammered shield lichen,[79] wax paper lichen[80] often served as nesting material for different birds like hummingbirds and finch birds (*Fringilla coelebs*) thereby providing camouflage to save the bird's nest from predators.[81] The lichen is also used for dyeing wool to create a distinct variety of hues, ranging from clear yellow to yellowish and dark, even rusty brown.[82]

CONCLUSION

Parmelia sulcata Taylor has an inherent capacity to bioaccumulate metal ions from the surroundings thereby serving as potential tool for biomonitoring research, particularly in air pollution. This lichen can accumulate high concentrations of heavy metals changing at morphological and physiological levels via various mechanisms. Over time, there has been a notable evolution in the understanding and application of this lichen in the context of biomonitoring, suggesting a prominent role as a biosensor.

The utilization of *P. sulcata* as a medicinal lichen has developed over the years and research data reveals its pharmacological potential as anti-cancer, anti-microbial, anti-fungal, antioxidant and mosquitocidal attributed to the presence of distinct chemical constituents. However, more scientific studies are required to assess the chemical constituents and pharmacological profile of this species.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ABBREVIATIONS

PAH: Polycyclic aromatic hydrocarbons; **POP:** Persistent organic pollutants; **INAA:** Instrumental neutron activation analysis; **RXRFA:** Radionuclide X-ray fluorescence analysis; **PIXE:** Particle induced X-ray emission; **ICP-OES:** Inductively coupled plasma optical emission spectroscopy; **A549:** Hypotriploid alveolar basal epithelial cell; **PC3:** Human prostate cancer cell line; **Hep3B:** Liver cancer cell line; **C6:** Rat glioma cell line; **GCXGC-TOF/MS:** Gas chromatography coupled with time-of-flight mass spectrometry; **MCF-7:** Human breast cancer cell line; **MDA-MB-231:** Human breast cancer cell line; **Ps-AgNPs:** Silver nanoparticles; **NIH-3T3:** Embryonic mouse fibroblast cell line; **GBM:** Glioblastoma multiforme; **HPLC:** High-performance liquid chromatography; **T98G:** Glioblastoma multiform tumor; **DPPH:** 2,2-diphenyl-1-picrylhydrazyl; **AuNPs:** Gold nanoparticles.

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