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REVIEW ARTICLE

BRYOPHYTES AS CANDIDATES FOR ANTIBIOTIC DISCOVERY: A REVIEW WITH EMPHASIS ON INDIAN SPECIES

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Abstract: Bryophytes are second-largest group of terrestrial plants, comprising more than 24,000 species. They occupy nearly every terrestrial habitat except the sea. Although they lack the physical barriers of vascular plants, they are rarely damaged by herbivores or pathogens. This resilience is attributed to their production of a wide range of secondary metabolites that also protect them against abiotic stresses. Several extracts and isolated compounds from bryophytes have been reported to inhibit fungi and both Gram-negative and Gram-positive bacteria. Bryophytes have long been used medicinally in China for diseases of bacterial origin; their use elsewhere, however, is uncommon and the chemical and pharmacological profiles of most species remain undisclosed. In India, bryological research has traditionally concentrated on systematics and the antimicrobial research is comparatively recent. This review examines the antimicrobial evidence for bryophytes, with emphasis on studies of Indian species. The review also assesses what is required to move from crude-extract screening to validated leads. In vitro inhibition by crude extracts is an initial screening result, not evidence of therapeutic efficacy and bryophytes are therefore best considered as candidates for further study rather than as established antibiotic sources.

Keywords: Antimicrobial activity, Antibiotic, Bryophytes, Secondary metabolites

INTRODUCTION

Bryophytes are a diverse group of nonvascular plants, which reproduce by spores rather than seeds. They include three clades namely liverworts (Marchantiophyta), hornworts (Anthocerotophyta) and mosses (Bryophyta) and constitute the second largest group of terrestrial plants (Dziwak *et al*., 2022; Benek *et al.*, 2025). Bryophytes collectively comprise more than 24,000 species (Sabovljevic *et al*., 2016; Benek *et al*., 2025). However, the number of taxa continues to change due to synonymization of some species and discovery of new ones (Benek *et al*., 2025). The characteristic feature of the bryophyte life cycle is the alternation of generations with the dominance of the haploid gametophyte. The sporophyte generation is diploid and short lived (Horn *et al*., 2021).

Bryophyte species constitute a significant part of the plant biodiversity. They occur across a wide range of terrestrial ecosystems, with the exception of marine ones. They can be easily found in diverse environments, including tropical forests, Antarctica, deserts and locations that are difficult for many other plant groups to colonize. Tolerance of low-light conditions enables them to grow even in dark environments such as caves (Dziwak *et al*., 2022). Although bryophytes lack well-developed physical defense-barriers unlike higher plants, they are hardly ever damaged by herbivores or pathogens. This is due to their ability to produce a wide range of secondary metabolites which allow them to survive unfavorable abiotic conditions and also protect them against many biotic stresses (Dziwak *et al*., 2022). In fact, the long evolutionary history of bryophytes has given them a wide collection of secondary compounds that serve as chemical defenses. The production of these compounds costs them metabolic energy; some bryophytes are edible and others do not (Glime, 2006).

Secondary metabolites of bryophytes and their antimicrobial potential

Bryophytes are rarely used as food. However, some species have a long history of their medicinal use, particularly in China. Their medicinal use is, however, less common elsewhere (Vollar *et al*., 2018). The ability to tolerate extreme environmental conditions allows bryophytes to produce rich and unique secondary metabolites. More than 400 novel chemical compounds had been isolated and structurally elucidated from bryophytes, despite the fact that only about 3.2% of mosses and 8.8% of liverworts had been chemically investigated (Greeshma *et al*., 2017). This clearly indicates that the group is understudied in this area. Nevertheless, due to their rich secondary metabolite content, bryophytes have attracted scientific attention in recent years (Coteli *et al*., 2026). Studies to date have identified a wide range of phenolic compounds, terpenoids, fatty acid derivatives and alkaloids from

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this group of tiny plants. While, there is extensive terpenoid diversity, the alkaloids occur only rarely in bryophytes (Dziwak *et al*., 2022; Kulshrestha *et al*., 2022).

The available literature indicates that from a phytochemical and pharmacological perspective, vascular plants have been explored far more extensively than bryophytes. On the other hand, the chemical and pharmacological profiles of most bryophyte species remain poorly understood. Bryophytes grow in an unfavorable environment as the earliest land plants and inevitably biosynthesize secondary metabolites to counter biotic and abiotic stresses. These secondary metabolites not only defend them against plant competition, microbial attack and insect or animal predation, but also function in UV protection, drought tolerance and freezing survival (Xie & Lou, 2009). The protective roles of these metabolites are particularly relevant to antibiotic discovery. This is because many of the same compounds that shield bryophytes from stresses may also display antibacterial and antifungal activity in laboratory assays. These compounds and their bioactivity need to be studied in greater depth.

Table 1. Potential biological activities of major secondary-metabolite classes reported in bryophytes. (Adapted from Dziwak *et al*., 2022).

Secondary-metabolite class	Potential activities reported
Benzenoids	Antibacterial and antifungal; insecticidal and molluscicidal; anti-UV
Bibenzyls and bis(bibenzyls)	Antibacterial and antifungal; cytotoxic; insecticidal and molluscicidal; phytotoxic; drought tolerance
Fatty acid derivatives	Antibacterial and antifungal; cold tolerance
Flavonoids	Antibacterial and antifungal; phytotoxic; anti-UV
Phenylpropanoids	Insecticidal and molluscicidal; cold tolerance; anti-UV
Terpenes and terpenoids	Antibacterial and antifungal; cytotoxic; insecticidal and molluscicidal; phytotoxic

Consistent with this, bryophytes appear to be rich sources of antimicrobial compounds. This is evidenced by several studies reporting antibacterial and antifungal activity in extracts of many moss and liverwort species (Vollar *et al*., 2018; Benek *et al*., 2025). For instance, McCleary and co-workers (1960) reported antibacterial effects in *Anomodon rostratus*, *Orthotrichum rupestre*, and *Plagiomnium cuspidatum*. Later in 1979, Banerjee and Sen found that 56% of 52 species inhibited at least one of eight test bacteria. Antimicrobial activity has also been reported in species from the genera *Bazzania*, *Conocephalum*, *Diplophyllum*, *Dumortiera*, *Marchantia*, *Metzgeria*, *Lunularia*, *Pellia*, *Plagiochila*, *Porella*, *Radula* and *Riccardia* (Baek *et al*., 2004; Kim *et al*., 2007). Figueiredo and co-workers (2002) proposed that essential oils contribute to the antimicrobial activity of liverworts, although active compounds have also been identified in non-volatile extracts. For example, sacculatal from *Pellia endiviifolia* was reported to act against *Streptococcus mutans*, and lepidozenolide from *Lepidozia fauriana* showed activity against methicillin-resistant *Staphylococcus aureus*. Marchantins from *Marchantia* species have also shown activity against several pathogenic bacteria (Asakawa, 1990; Shu *et al*., 1994; Scher *et al*., 2002). Herbertane sesquiterpenoids were active against *Staphylococcus aureus*, *Klebsiella pneumoniae* and *Bacillus subtilis* (Harinantenaina & Asakawa, 2004; Komala *et al*., 2010). Chlorinated bibenzyls from *Riccardia marginata* inhibited *Bacillus subtilis*, while diterpenoids from *Jungermannia exertifolia* showed activity against *Mycobacterium tuberculosis* H37Rv (Baek *et al*., 2004; Scher *et al*., 2010).

Olofin (2013) tested extracts from ten bryophytes (*Radula flacida*, *Cyatodium africanum*, *Frullania spongiosa*, *Thuidium gratum*, *Ectropothecium aeruginosum*, *Sematophyllum caespitosum*, *Stereophyllum radiculosum*, *Babula lamberenensis*, *Campylopus aspericuspis* and *Calymperes erosum*) and found that fractions obtained from *Cyatodium africanum* and *Radula flacida* exhibit antimicrobial activity against some pathogenic microorganisms. In the light of this, *Cyatodium africanum* and *Radula flacida* that are effective can be recommended as sources of antimicrobial agents in the treatment of some diseases caused by these etiological agents (Olofin, 2013). Bryophyte extracts and isolated compounds have also shown in vitro cytotoxic activity against cancer cell lines. For example, terpenoids and bibenzyl derivatives are among the compounds that are reported to be most active (Dey & Mukherjee, 2015). Christchellyn and fellow researchers (2020) tested ethanol extracts of a moss *Orthostichella rigida* against strains of Gram-negative (*Escherichia coli* and *Salmonella enteritidis*), Gram-positive bacteria (*Salmonella aureus* and *Listeria monocytogenes*) and yeast fungi (*Candida albicans* and *Candida neoformans*) and reported that all extracts presented antimicrobial activity. The extensive chemical diversity, alongside evidence that bryophyte cultures grown in vitro can produce substances with antibiotic activity, positions bryophytes as promising candidates for extensive antimicrobial screening (Olasoji *et al*., 2019).

Antimicrobial studies on Indian bryophytes

Studies from India also provide several examples of antimicrobial activity in bryophytes. These reported studies are mostly limited to crude extracts and a small number of species. Earlier Indian bryologists mainly focused on the systematics of bryophytes and therefore, no significant work in the past has investigated antimicrobial activity. However, few researchers, namely, Subramoniam & Subhisha (2005), Bodade *et al*., 2008 and Deora & Guhil (2014; 2018) have investigated the antimicrobial activities of mosses. In fact, mosses are the most studied, followed by thalloid and leafy liverworts (Shete *et al*., 2024). In a study conducted by Dhondiyal and co-workers (2013), extracts of the liverwort *Lunularia cruciata* from the Kumaon Himalaya were investigated for antibiotic potential. The results indicated that all the bacterial strains were sensitive to the tested extracts of *Lunularia cruciata* except the aqueous extract. Among the several species tested against various microbes, *Conocephalum conicum* showed the strongest bioactivity. In another investigation, mosses collected in the Eastern Himalaya, particularly *Syrrhopodon subconfertus*, inhibited both Gram-positive and Gram-negative bacteria and also exhibited antioxidative potential (Mukhopadhyay, 2013). Similarly, methanol or dichloromethane extracts of the liverworts *Plagiochasma intermedium*, *Asterella wallichiana* and *Targionia hypophylla* collected from Kolhapur district were reported to inhibit all bacterial growth in agar-well diffusion assays (Sawant & Karadge, 2010).

In another significant study, which also claims to be the first report on the antimicrobial activity of Indian mosses, extract of *Thuidium cymbifolium*, *Thuidium delicatulum*, *Bryum cellulare*, *Bryum argentium* and *Plagiochasma appendiculatum* showed antimicrobial activity against test microorganisms (Bodade *et al*., 2008). The results of this study showed that gram negative microorganisms are more sensitive than Gram positive microorganisms. Conventionally, we know that, antibiotics are generally more active against Gram positive than Gram negative bacteria. However, mosses studied by these workers were found to be active against Gram negative bacteria. This demonstrates the potential of selected bryophytes as antimicrobial agents. Bodade *et al*. (2008) also claim that while most research studies revealed no antifungal activity of Indian bryophytes, their study showed that all the selected fungi were more or less sensitive to all the bryophyte fractions. Many subsequent Indian studies have screened local bryophytes against bacterial and fungal pathogens. For instance, researchers in the Kumaun Himalaya in vitro tested extracts of the liverworts *Reboulia hemisphaerica* and *Marchantia palmata* and the moss *Hydrogonium gracilantum* and the extracts were reported to inhibit pathogens such as *Escherichia coli*, *Bacillus cereus*, *Erwinia chrysanthemi* and *Pseudomonas aeruginosa* (Kandpal *et al*., 2016).

Results from almost all these and several other studies, do not indicate that the extracts or fractions themselves yield a purified antibiotic. In fact, based on the available sources, no bryophyte-derived commercially available antibiotic has yet reached clinical use. However, many potential bioactive candidates derived from several species of bryophytes are undergoing continued preclinical evaluation. For instance, several workers have isolated metabolites such as lunularin and marchantin A and many other (Table 2). Their activity observed in crude extracts or fractions is, however, preliminary. Consequently, their critical evaluation is essential for determining whether bryophyte derived metabolites can contribute to future antimicrobial therapy and eventually antibiotic usage. Future work should therefore focus on bioprospecting of bryophytes through standardized, reproducible screening pipelines that link chemical characterization to antimicrobial activity (Greeshma *et al*., 2017).

Table 2. Antibacterial activity of bryophyte extracts and isolated compounds against selected human pathogenic bacteria (Adapted from Cianciullo *et al*., 2021)

Bacterial species	Antibacterial compound/extract	Compound class	Bryophyte species
Staphylococcus aureus	α-herbertenol	Sesquiterpenoids	*Mastigophora diclados*
	β-herbertenol		
	herbertene-1,2- diol		
	mastigophorene C		
	α-formyl herbertenol		
	Perrotettin A-D	bibenzyl	*Marchantia polymorpha*
	Perrotettin F		*Lunularia cruciata*
	Marchantin A		*Marchantia polymorpha*
	Lepidozenolide	Sesquiterpenoids	*Lepidozia fauriana*

Pseudomonas aeruginosa	Marchantin A	bibenzyl	*Marchantia* spp.
	Bartramiaflavone	Flavonoids	*Bartramia pomiformis*; *Hedwigia ciliata*; *Plagiomnium cuspidatum*; *Plagiomnium affine*; *Dicranum scoparium*
	Lucenin-2		
	Saponarin		
	Apigenin		
	Apigenin-7-O-triglycoside		
	Lunularin	bibenzyl	*Dumortiera hirsute*
	Perrotettin F	bibenzyl	*Lunularia cruciata*
	Bartramiaflavone	Flavonoids	*Bartramia pomiformis*; *Hedwigia ciliata*; *Plagiomnium cuspidatum*; *Plagiomnium affine*
	Lucenin-2		
	Saponarin		
	Apigenin		
Escherichia coli	Apigenin	Flavonoids	*Plagiomnium affine*; *Dicranum scoparium*; *Plagiomnium cuspidatum*; *Hedwigia ciliata*
	Vitexin		
	Saponarin		
	Lucenin-2		
	Marchantin A	bibenzyl	*Marchantia* spp.
Enterobacter spp.	Bartramiaflavone;	Flavonoids	*Bartramia pomiformis*; *Hedwigia ciliata*; *Plagiomnium cuspidatum*; *Plagiomnium affine*; *Dicranum scoparium*
	Luteolin-7-O-neohesperoside;		
	Lucenin-2;		
	Saponarin;		
	Apigenin-7-O-triglycoside;		
	Apigenin		

DISCUSSION

The historical records demonstrate the persistent interest in antimicrobial activity of bryophytes. Indigenous communities around the world have been using bryophytes for antimicrobial, antipyretic, dermatological, hepatic, cardiovascular and wound-healing purposes (Benek *et al*., 2025). They have been used in traditional medicine for centuries and approximately 70 species have established medicinal applications (Motti *et al*., 2023). Extracts obtained from them have demonstrated activity against microbial pathogens of humans and plants, plant-pathogenic fungi and insect pests, as well as allelopathic effects (Kulshrestha *et al*., 2022). Certain preliminary reports appeared in the 1940s and then studies in the 1950s drew attention to the antibacterial effects of *Anomodon rostratus*, *Orthotrichum rupestre* and *Plagiomnium cuspidatum*. A comprehensive study published in 1979 assessed 52 species against eight bacterial strains and found that 56% were active against at least one test bacterium (Vollar *et al*., 2018). A subsequent survey estimated that nearly 200 bryophyte species had been screened, with 63–76% producing positive results (Shete *et al*., 2024). Nevertheless, the phytochemical and pharmacological properties of most species remain unknown (Vollar *et al*., 2018). This indicates that the expansion of screening studies has not been matched by comparable progress in chemical characterization. However, several recent works have identified molecules associated with the observed bioactivity. Some of these are macrocyclic bis(bibenzyls):

marchantin A and perrottetin A–F; the bibenzyl lunularin; the glycosylated flavonoids luteolin-7-*O*-neohesperoside, apigenin-7-*O*-triglycoside and saponarin; the flavonoids apigenin, lucenin-2 and bartramiaflavone; and the sesquiterpenoids α-herbertenol, β-herbertenol, herbertene-1,2-diol, mastigophorene C, α-formyl herbertenol and lepidozenolide. These compounds have shown activity ranging from weak to strong against several human bacterial pathogens (Cianciullo *et al*., 2021). Table 2 brings together extract and compound-level evidence of antibacterial activity in some of the species.

Minimum inhibitory concentration (MIC) is the lowest concentration of a substance that effectively inhibits visible bacterial growth. Vidal *et al*. (2012) noted that an ethanol extract of *Octoblepharum albidum* stopped the growth of *Escherichia coli* ATCC 25922 and *Klebsiella pneumoniae* ATCC 33018 at an MIC of 512 µg/mL. When the extract was tested together with aminoglycosides, a family of antibiotics that includes gentamicin and kanamycin, the amount of each antibiotic needed to stop growth decreased. The largest reduction was with the extract plus gentamicin against *Escherichia coli* and the extract plus kanamycin against *Klebsiella pneumoniae*, where the MIC dropped from 128 to only 32 µg/mL. These results are encouraging because both Gram-negative and Gram-positive bacteria are rapidly becoming resistant to nearly all the antibiotics presently available (Cianciullo *et al*., 2021). Some reviews also report that Gram-negative bacteria are more sensitive to bryophyte extracts than to the conventional antibiotics, which usually work better against Gram-positive bacteria. On this basis, bryophyte extracts have been suggested as possible partners for existing antibiotics, a pattern that is rare in higher plants (Dziwak *et al*., 2022). This interaction suggests a valuable area for further investigation.

A report of antimicrobial activity in Indian mosses found that *Escherichia coli* and *Staphylococcus aureus* were the most susceptible test organisms, followed by *Pseudomonas aeruginosa* and *Klebsiella pneumoniae*. Its authors also concluded that Gram-negative microorganisms were more sensitive than Gram-positive ones, in contrast to the reported pattern for conventional antibiotics (Bodade *et al*., 2008). In addition, results from the Kumaun screening study are broadly consistent with this observation when assessed by MIC test. Kandpal *et al*. (2016) reported that the ethanolic extract of *Hydrogonium gracilantum* had MICs of 1.94 µg/mL against *Erwinia chrysanthemi* and 3.91 µg/mL against *E. coli*. On the other hand, ethanolic *Reboulia hemisphaerica* extract had MICs of 3.91 µg/mL against *Pseudomonas aeruginosa* and 7.81 µg/mL against *E. coli*. However, the authors also noted that some of these low MIC values were not fully consistent with the corresponding zone of inhibition results, warranting cautious interpretation of the reported antibacterial potency. Other findings, however, point in a different direction. Chloroform fractions of liverworts were more active against Gram-negative strains, whereas butanol fractions of mosses showed substantial activity against Gram-positive bacteria (Singh *et al*., 2011). Another study on *Platyphylla* and *Dicranum scoparium* likewise reported activity against the Gram-positive bacteria *Bacillus subtilis*, *Staphylococcus aureus* and *Sarcina lutea*, but not against the Gram-negative bacterium *E. coli* (Yayintas & Irkin, 2018). Taken together, these results suggest that susceptibility depends on the bryophyte taxon, extraction solvent and the test organism, rather than on Gram status alone. As shown in Table 2, chloroform extracts from different species of the same organism vary several-fold in potency. In addition, the activity of *Lunularia cruciata* followed the order ethanol > methanol > acetone > chloroform, while its aqueous extract was inactive (Dhondiyal *et al*., 2013). Greater activity against Gram-negative bacteria should therefore be treated as a hypothesis to test for each extract, rather than as a general property of bryophytes. This qualification is also important especially for Indian taxa, which have been investigated only recently and unevenly.

Historically, Indian bryology focused primarily on systematics. Antimicrobial research remains concentrated among a small number of groups, including Subramoniam & Subhisha (2005), Bodade *et al*. (2008) and Deora & Guhil (2014, 2018). Thalloid and leafy liverworts even received far less attention than mosses (Shete *et al*., 2024). Nevertheless, Indian medicinal traditions may provide a relevant ethnopharmacological basis for further work in this field. This is because liverworts have long been used to treat hepatitis and skin disorders (Gahtori & Chaturvedi, 2019). When considered collectively, Indian bryophyte studies establish three main points. First, antimicrobial activity is widespread but not universal. For instance, thirteen of the 16 Marchantiales species tested were inhibitory and the five species of Rebouliaceae showed mainly marked antibiotic activity (Shete *et al*., 2024). Among bryophytes examined in Kolhapur district, *Targionia hypophylla* showed the most promising activity, whereas *Cyathodium cavernarum* was comparatively inactive (Sawant & Karadge, 2010). Second, potency varies substantially. Scientists reported that MIC, MBC and MFC values across 14 species ranged from 3.91 to 500 µg/mL. *Conocephalum conicum* showed the greatest bioactive potential, followed by *Marchantia papillata* and *Anoectangium thomsonii*. Third, very few of these studies have isolated a purified compound, identified or characterized the biomolecules responsible for the observed antimicrobial activity.

These findings are crucial and also point to four priorities. First, research should now move beyond additional crude-extract screening towards bioassay-guided fractionation, so that activity can be attributed to defined compounds. Second, studies should report extraction procedures, yields, chemical fingerprints and reproducibility alongside MIC and MBC values, strain identities, controls and replicate data. Such standardized reporting would enable comparisons among Indian taxa and with bryophytes studied elsewhere. Third, extracts and compounds should be tested against clinically relevant drug-resistant pathogens. Fourth, field-collected plant material should be compared with sterile, microbe-free axenic cultures maintained in the laboratory. Since *in vitro* bryophyte cultures have been shown to synthesize antibiotic substances (Olasoji *et al*., 2019), this comparison will allow researchers to confirm whether the plant itself is creating the antibiotic effect or whether microbes living inside the wild plant are producing it. To further advance these efforts, combination testing should also complement the studies of individual compounds. Bryophyte antimicrobial activity may depend not only on chemical composition, structural configuration or functional groups, but also on synergistic or antagonistic interactions among these compounds (Gahtori & Chaturvedi, 2019). The findings for *O. albidum* illustrate the relevance of such interactions, as its extract modified antibiotic activity rather than relying solely on its intrinsic antibacterial potency (Vidal *et al*., 2012). At the compound level, bioassay-guided fractionation of *Mastigophora diclados* provides a useful model. Among the herbertane sesquiterpenoids, mastigophorene C produced the strongest reported antibacterial effect, with a 17 mm inhibition zone, whereas its monomer, herbertene-1,2-diol, produced a 13 mm inhibition zone (Novakovic *et al*., 2021). These researchers also noticed that crude ether and methanol extracts inhibited *B. subtilis* and *S. aureus* at an MIC of 16 µg/mL and subsequent fractionation yielded compounds that showed moderate activity against *B. subtilis*, with MICs of 2–8 µg/mL. These comparisons may only work if researchers use the same testing methods and pathogenic strains. If the laboratory setups are different, it is impossible to tell whether the results changed because of the unique chemistry of the plant extract or simply because the experiment was run differently.

Overall, the evidence supports a more qualified and useful conclusion than either unreserved optimism or complete dismissal. Bryophytes constitute a therapeutically promising group of plants whose phytochemicals may yield drug leads and *in vitro* culture may facilitate the production and isolation of these compounds at larger scales (Das *et al*., 2022). However, most of the evidence reviewed here identifies candidates rather than establishing sources of antibiotics. This is irrefutably because antibacterial activity of crude extracts observed *in vitro* is an initial screening result, not proof of therapeutic efficacy. In fact, no antibiotic in clinical use has been confirmed to originate from bryophytes (Dziwak *et al*., 2022). To date, *in vivo* studies of bryophyte extracts and compounds have focused on anti-inflammatory, antinociceptive, wound-healing, anticarcinogenic, nanoparticle pharmacokinetic and antilipidemic endpoints (Cianciullo *et al*., 2021). Antibacterial efficacy in an infection model has not been demonstrated or published yet. Further progress will require a staged evaluation which may include purification and identification of active compounds and testing against mammalian cells. Moreover, crude plant extracts may contain toxic constituents and cannot be presumed safe; the selective compound assessment in relevant infection models is crucial for efficacy, mechanism of action, toxicity and pharmacokinetics. In each case, extraction methods, chemical characterization and reproducibility should also be reported alongside MIC values.

CONCLUSION

Bryophytes have been screened for antimicrobial activity since the 1940s, and the results are encouraging enough to keep looking. Since then, researchers around the globe have identified many of the molecules behind this activity. Indian work also fits this picture and has begun contributing to this research. Bryology in India has moved from systematics towards antimicrobial screening under proper controls. In vitro inhibition by a crude extract is a starting point, not proof that a plant can treat an infection. No clinically used antibiotic has yet been confirmed to come from any bryophyte. Several bryophyte extracts have demonstrated appreciable *in vitro* antibacterial activity; their potency, however, varies with species, extract solvent, concentration used and test organism. Some of the evidence reviewed also indicates that when a bryophyte extract is tested along with a low dose of ordinary antibiotics, the antibiotics show substantially greater effectiveness. This evidence of antibiotic potentiating activity in selected bryophytes also warrants further investigations. Such a finding may be the most promising lead so far and it is distinct from finding a new antibiotic. Hence, the way forward is straightforward, if slow. New active compounds need to be extracted, purified and identified. The identified compounds should then be tested for their toxicity against human cells and those showing acceptable selectivity should be further evaluated in suitable infection models.

DECLARATION

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REFERENCES

Asakawa, Y. (1990). Biologically active substances from bryophytes. In R. N. Chopra and S. C. Bhatla, *Bryophyte development: Physiology and biochemistry* (pp. 259–287). CRC Press.
Google Scholar

Baek, S.H., Phipps, R. K. and Perry, N. B. (2004). Antimicrobial chlorinated bibenzyls from the liverwort *Riccardia marginata*. *Journal of Natural Products*, **67**, 718–720.
Google Scholar

Banerjee, R. D. and Sen, S. P. (1979). Antibiotic activity of bryophytes. *The Bryologist*, **82**, 141–153.
Google Scholar

Benek, A., Turu, D., Bozyel, M. E., Simsek, O. and Canli, K. (2025). The Secondary Metabolites of Bryophytes and Their Therapeutic Applications. In *IGI Global eBooks* (pp. 557–588). IGI Global. https://doi.org/10.4018/979-8-3693-9112-9.ch014
Google Scholar

Bodade, R. G., Borkar, P. S., Arfeen, S. and Khobragade, C. N. (2008). In vitro Screening of Bryophytes for Antimicrobial Activity. *DOAJ (DOAJ: Directory of Open Access Journals)*. https://doaj.org/article/8538f60a0ead4171adb5ac1727f75a7d
Google Scholar

Christchellyn, K. R., Enio, L. J., Eduardo, M. E., Talita, S., Buhl, B., Neusa, F. de M. and Bordin, J. (2020). Evaluation of the antimicrobial activity of ethanol extracts from *Orthostichella rigida* (Mull. Hal.) B.H Allen Magill (Bryophyta) on pathogenic microorganisms. *Journal of Medicinal Plants Research*, *14*(3), 98–104. https://doi.org/10.5897/jmpr2019.6816
Google Scholar

Cianciullo, P., Maresca, V., Sorbo, S. and Basile, A. (2021). Antioxidant and Antibacterial Properties of Extracts and Bioactive Compounds in Bryophytes. *Applied Sciences*, **12**(1), 160. https://doi.org/10.3390/app12010160
Google Scholar

Coteli, E., Erdem, B. and Alatas, M. (2026). Bioactive Potential of *Pohlia wahlenbergii* (Bryophyta): Antioxidant, Antidiabetic, and Antimicrobial Activities. *Anatolian Bryology*, **12**(1), 50–59. https://doi.org/10.26672/anatolianbryology.1954783
Google Scholar

Das, K., Kityania, S., Nath, R., Das, S., Nath, D. and Talukdar, A. D. (2022). Bioactive Compounds from Bryophytes. In *Reference series in phytochemistry* (pp. 1–15). Springer International Publishing. https://doi.org/10.1007/978-3-030-97415-2_2-1
Google Scholar

Deora, G. and Guhil, N. (2014). In vitro antifungal activity of *Bryum capillare* (a moss) extract against *Drechslera maydis*. *International Journal of Pharmaceutical Research and Bio-Science*, **3**(5), 268–275.
Google Scholar

Deora, G. S. and Guhil, N. (2018). Comparative study on the extract of *Bryum argenteum* and synthetic fungicide against some common diseases of *Zea mays*. *International Journal of Life Sciences*, **6**(1), 217–221.
Google Scholar

Dey, A. and Mukherjee, A. (2015). Therapeutic potential of bryophytes and derived compounds against cancer. *Journal of Acute Disease*, **4**, 236–248.
Google Scholar

Dhondiyal, P. B., Neerja, P. and Bargali, K. (2013). Antibiotic potential of *Lunularia cruciata* (L.) Dum ex. Lindb (bryophyta) of Kumaon Himalaya. *African Journal of Microbiology Research*, **7**(34), 4350–4354. https://doi.org/10.5897/ajmr12.1256
Google Scholar

Dziwak, M., Wroblewska, K., Szumny, A. J. and Galek, R. (2022). Modern Use of Bryophytes as a Source of Secondary Metabolites. *Agronomy*, **12**(6), 1456. https://doi.org/10.3390/agronomy12061456
Google Scholar

Figueiredo, A. C., Sim-Sim, M., Barroso, J. G., Pedro, L. G., Santos, P. A. G., Fontinha, S. S., Schripsema, J., Deans, S. G. and Scheffer, J. J. C. (2002). Composition of the essential oil from the liverwort *Marchesinia mackaii* S. F. Gray grown in Portugal. *Journal of Essential Oil Research*, **14**, 439–442.
Google Scholar

Gahtori, D. and Chaturvedi, P. (2019). Bryophytes: A Potential Source of Antioxidants. In *IntechOpen eBooks*. IntechOpen. https://doi.org/10.5772/intechopen.84587
Google Scholar

Greeshma, G.M., Manoj, G.S. and Murugan, K. (2017). Insight into Pharmaceutical importance of Bryophytes. *Kongunadu Research Journal*, **4**(2), 84–88. https://doi.org/10.26524/krj208
Google Scholar

Glime, J. M. (2006). Bryophytes and herbivory. *Cryptogamie, Bryologie*, **27**(1), 191–203.
Google Scholar

Harinantenaina, L. and Asakawa, Y. (2004). Chemical constituents of Malagasy liverworts, part II: Mastigophoric acid methyl ester of biogenetic interest from *Mastigophora diclados*. *Chemical and Pharmaceutical Bulletin*, **52**, 1382–1384.
Google Scholar

Horn, A., Pascal, A., Loncarevic, I., Marques, R. V., Lu, Y., Miguel, S., Bourgaud, F., Porsteinsdottir, M., Cronberg, N., Becker, J. D., Reski, R. and Simonsen, H. T. (2021). Natural Products from Bryophytes: From Basic Biology to Biotechnological Applications. *Critical Reviews in Plant Sciences*, **40**(3), 191–217. https://doi.org/10.1080/07352689.2021.1911034
Google Scholar

Kandpal, V., Chaturvedi, P., Negi, K., Gupta, S. and Sharma, A. (2016). Evaluation of Antibiotic and Biochemical Potential of Bryophytes from Kumaun Hills and Tarai Belt of Himalayas. *International Journal of Pharmacy and Pharmaceutical Sciences*, **8**(6), 65–69. https://innovareacademics.in/journals/index.php/ijpps/article/view/10516
Google Scholar

Komala, I., Ito, T., Nagashima, F., Yagi, Y. and Asakawa, Y. (2010). Cytotoxic, radical scavenging and antimicrobial activities of sesquiterpenoids from the Tahitian liverwort *Mastigophora diclados* Nees. *Journal of Natural Medicines*, **64**, 417–422.
Google Scholar

Kim, S. J., Park, H. R., Park, E. and Lee, S. C. (2007). Cytotoxic and antitumor activity of momilactone B from rice hulls. *Journal of Agricultural and Food Chemistry*, **55**, 1702–1706.
Google Scholar

Kulshrestha, S., Jibran, R., Klink, J. W. van, Zhou, Y., Brummell, D. A., Albert, N. W., Schwinn, K. E., Chagne, D., Landi, M., Bowman, J. L. and Davies, K. M. (2022). Stress, senescence, and specialized metabolites in bryophytes. *Journal of Experimental Botany*, **73**(13), 4396–4411. https://doi.org/10.1093/jxb/erac085
Google Scholar

McCleary, J. A., Sypherd, P. S. and Walkington, D. L. (1960). Mosses as possible sources of antibiotics. *Science*, **131**, 108.
Google Scholar

Motti, R., Palma, A. D. and Falco, B. de. (2023). Bryophytes Used in Folk Medicine: An Ethnobotanical Overview. *Horticulturae*, **9**(2), 137. https://doi.org/10.3390/horticulturae9020137
Google Scholar

Mukhopadhyay, S. K. (2013). Screening of Antimicrobial and Antioxidative Potential of Selected Eastern Himalayan Mosses. *European Journal of Medicinal Plants*, **3**(3), 422–428. https://doi.org/10.9734/ejmp/2013/3164
Google Scholar

Novakovic, M., Ludwiczuk, A., Bukvicki, D. and Asakawa, Y. (2021). Phytochemicals from bryophytes: Structures and biological activity. *Journal of the Serbian Chemical Society*, **86**(12), 1139–1175. https://doi.org/10.2298/jsc211027100n
Google Scholar

Olasoji, K. O., Makinde, A. M., Akinpelu, B. A., Igbeneghu, O. A. and Isa, M. O. (2019). Antimicrobial Activity of Selected Mosses on Obafemi Awolowo University Campus, Ile-Ife, Nigeria. *Notulae Scientia Biologicae*, **11**(3), 462–466. https://doi.org/10.15835/nsb11310439
Google Scholar

Olofin, O. (2013). Assessment of the antimicrobial properties of fractions obtained from bryophytes. *Journal of Microbiology and Antimicrobials*, **5**(5), 50–54. https://doi.org/10.5897/jma11.055
Google Scholar

Sabovljevic, M., Sabovljevic, A., Ikram, N. K. K., Peramuna, A., Bae, H. and Simonsen, H. T. (2016). Bryophytes – an emerging source for herbal remedies and chemical production. *Plant Genetic Resources*, **14**(4), 314–327. https://doi.org/10.1017/s1479262116000320
Google Scholar

Sawant, U. J. and Karadge, B. A. (2010). Antimicrobial activity of some bryophytes (liverworts and a hornwort) from Kolhapur district. *Pharmacognosy Journal*, **2**(16), 29–32. https://doi.org/10.1016/s0975-3575(10)80046-x
Google Scholar

Shete, R. S., Wangikar, H., Chavan, J., Kanade, M. B. and Chavan, S. J. (2024). Bioactive Compounds of Bryophytes: Unveiling Antimicrobial Properties and Therapeutic Potential. *International Journal of Plant and Environment*, **10**(3). https://doi.org/10.18811/ijpen.v10i03.01
Google Scholar

Shu, Y. F., Wei, H. C. and Wu, C. L. (1994). Sesquiterpenoids from liverworts *Lepidozia vitrea* and *L. fauriana*. *Phytochemistry*, **37**, 773–776.
Google Scholar

Scher, J. M., Burgess, E. J., Lorimer, S. D. and Perry, N. B. (2002). A cytotoxic sesquiterpene and unprecedented sesquiterpene-bisbibenzyl compounds from the liverwort *Schistochila glaucescens*. *Tetrahedron*, **58**, 7875–7882.
Google Scholar

Scher, J. M., Schinkovitz, A., Zapp, J., Wang, Y., Franzblau, S. G., Becker, H., Lankin, D. C. and Pauli, G. F. (2010). Structure and anti-TB activity of trachylobanes from the liverwort *Jungermannia exsertifolia* ssp. *cordifolia*. *Journal of Natural Products*, **73**, 656–663.
Google Scholar

Singh, M., Singh, S., Nath, V., Sahu, V. and Rawat, A. K. S. (2011). Antibacterial activity of some bryophytes used traditionally for the treatment of burn infections. *Pharmaceutical Biology*, **49**(5), 526–530. https://doi.org/10.3109/13880209.2010.523007
Google Scholar

Subramoniam, A. and Subhisha, S. (2005). Antifungal activities of a steroid from *Pallavicinia lyellii*, a liverwort. *Bioline International*, **37**(5), 304. https://doi.org/10.4103/0253-7613.16854
Google Scholar

Vidal, C. A. S., Sousa, E. O. de, Rodrigues, F., Campos, A., Lacerda, S. R. and Costa, J. G. M. da. (2012). Phytochemical screening and synergistic interactions between aminoglycosides, selected antibiotics and extracts from the bryophyte Octoblepharum albidum Hedw (Calymperaceae). *Archives of Biological Sciences*, **64**(2), 465–470. https://doi.org/10.2298/abs1202465v
Google Scholar

Vollar, M., Gyovai, A., Szucs, P., Zupko, I., Marschall, M., Csupor-Loffler, B., Berdi, P., Vecsernyes, A., Csorba, A., Liktor-Busa, E., Urban, E. Z. and Csupor, D. (2018). Antiproliferative and Antimicrobial Activities of Selected Bryophytes. *Molecules*, **23**(7), 1520. https://doi.org/10.3390/molecules23071520
Google Scholar

Xie, C. and Lou, H. (2009). Secondary Metabolites in Bryophytes: An Ecological Aspect. *Chemistry & Biodiversity*, **6**(3), 303–312. https://doi.org/10.1002/cbdv.200700450
Google Scholar

Yayıntas, O. T. and Irkin, L. C. (2018). Bryophytes as Hidden Treasure. *Health Sciences Quarterly*, **2**(1), 71–83. https://doi.org/10.26900/jsp.2018.07
Google Scholar