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Bryophytes as a safeguard of fruits from postharvest fungal diseases: A Review

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ABSTRACT: Postharvest losses from fungal pathogens to essential fruits and vegetables are enormous and alarming. Orthodox synthetic fungicides are being used as a regular practice to restrict these losses. However, now by knowing the hazards of these chemical-based fungicides, the situation demands alternative green technology. Consequently, many angiosperms plant extracts have been evaluated for their antifungal nature and achieved substantial success. However, the second most prevalent flora on land, i.e. bryophytes, have been scarcely used and somewhat remain neglected besides their remarkable thallus organization, water relations and antimicrobial potential. For postharvest fungus control, these bryophytes, the first land plants' extracts to be researched and promoted due to concerns about drug resistance, nephrotoxicity and biomagnification related to current synthetic fungicides. Since these amphibious plants have their unique protective mechanism against fungal or bacterial attacks due to their unique phytochemistry, therefore have great potential to be used as eco-friendly fungicides. Considering these factors, this article seeks to direct the attention of interested researchers toward the relatively accessible but vast underutilised bryo-diversity to investigate their remarkable potential as postharvest antifungal agents first in laboratories and then on a commercial scale in the future.

1. INTRODUCTION

Through continued evolution, plants have developed complex inherent resistance mechanisms against various pathogen assaults. Though plants have innate resistance mechanisms, they can augment the pathogen defense-related capacity by judging a range of biotic elicitors, viz., pathogen-induced molecules and chemical signals (Ahn et al., 2005). The researchers on plant defense are usually more inclined towards the flowering plants, and lower plants such as bryophytes are neglected in the recent past. This partiality towards the bryophytes was strange as this plant group is considered 'First land plants' and experienced more challenging environmental conditions than the most evolved plant group, i.e., angiosperms. Accepting this fact, many researchers have taken up these plants now to find out their antimicrobial potential, and they are attaining remarkable outcomes.

Being a major group of land plants, bryophytes occur in most ecosystems and substrates ranging from the Arctic to the Antarctic, desert, excluding the sea. Taxonomically, their placement is amid the Chlorophyceae algae and the pteridophytes (ferns). There are about 22,000-25,000 species worldwide, distributed in three lines (Mosses, Liverworts and Hornworts) exist (Söderström et al., 2016), the liverworts, i.e., Marchantiophyta (6000 species), the hornworts, i.e., Anthocerotophyta (300 species) and the mosses, the Bryophyta (14000 species). They are expected to have the closest kinship with the first terrestrial plants (Asakawa et al., 2013; Konrat et al., 2010).

Among the three lineages, usually, liverworts have been the preferred choice for their biochemical compounds compared to mosses and hornworts because of the occurrence of oil bodies (membrane-bound organelles) within the cells of the most liverworts, viz., *Marchantia* spp., *Riccia* spp., *Plagiochasma* spp., *Cyathodium* spp., *Plagiochila* spp., *Radula* spp., *Lophozia* spp., and *Jungermannia* spp. Usually, these oil bodies contain terpenoids suspended in a carbohydrate/protein-rich medium (Konrat et al., 2010).

Apart from liverworts, many mosses viz., *Anoectangium stracheyanum* Mitt., *Barbula arcuata* Griff., *Barbula javanica* Doz. et Molk., *Brachythecium populeum* (Hedw.) B.S.G., *Brachythecium rutabulum* (Hedw.) B.S.G., *Bryum capillare* Hedw., *Cratoneuron filicinum* (Hedw.) Spruc., Entodon cf. rubicundus (Mitt.) Jeag., *Entodon pulchellus* (Griff.) Jaeg., *Grimmia anodon* Bruch & Schimp., *Macrothamnium submacrocarpum* (Ren. et Card.), *Mnium marginatum* (With.) P. Beauv., *Physcomitrium pulchellum* (Griff.) Mitt., *Rhynchostegium vagans* Jaeg., *Sphagnum junghuhnianum* Doz. et Molk., *Trachypodopsis serrulata* (P. Beauv.) Fleisch., *Thuidium cymbifolium* (Doz.

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et Molk.), and *Tortella tortuosa* (Hedw.) Limpr. have also been evaluated for their biochemistry, and exciting results have been obtained (Elibol et al., 2011; Singh et al., 2007). While in the case of hornworts, the reports are rare, and only *Anthoceros* spp. have been evaluated for their antimicrobial phytoconstituents (Asakawa et al., 2013).

The vast diversity of bryophytes is available to be used in various ways for agriculture and horticulture food produce where the losses due to postharvest fungi-driven infections are very alarming. The harvested fruits and vegetables are prone to fungal infection during the packaging, transportation and shelfing. All the three mentioned stages have the problem of fungal infection due to moisture availability, and fungal spores are easily thrived due to this water content.

Since bryophytes are poikilohydric, they are susceptible to environmental changes, especially the nearby available water content and can be used both in wet and dry forms according to the macro-and micro-climatic requirement. They have excellent water holding and absorption capability, and the dry thalli can absorb water and moisture at a rapid rate. Once the thalli absorb the water, they release it very slowly (Glime, 2017). Therefore, the water relation of bryophytes is unique. This property is helpful to control the incidence of fungal attacks on harvested crops due to unwanted water/moisture in the surrounding fruits/vegetables during their transportation and shelfing.

This review provides an overview of bryophytes' roles in treating fungal infections, particularly postharvest fungi that can be employed in place of synthetic fungicides.

2. METHODOLOGY

Dependable and prevalent universal scientific databases such as Scopus, PubMed, Research Gate, Science Direct and Google Scholar were investigated using the quest threads such as "biochemical composition of bryophytes", "bioactivity of bryophytes", "anti-fungal bryophytes", etc., to retrieve various documents related to biochemistry and antifungal potential of bryophytes. The scientific names of the bryophytes and fungal strains were further validated from www.theplantlist.org.

3. POSTHARVEST DISEASES

Economic losses because of any postharvest infection may occur at any time for the duration of postharvest management, right from produce collection to its utilization. The prevalence of postharvest disease during handling usually demolishes the quantity and quality of affected products and increases the salable value in severe infections. In moderate cases of infection, at least the overall product value decreases (Benkeblia & Tennant, 2011). For instance, tarnished fruits that are not appropriate to sell fresh can be used for other purposes at a reduced amount. In many cases, the growers are even unable to get the finance spent on harvesting, casing and transportation. Therefore, postharvest infection causes health issues related to toxic foods and demolishes the overall economic gains. Numerous fungal genera, especially the species of Alternaria, *Fusarium* and *Penicillium*, are known to generate mycotoxins under factual circumstances (Tripathi et al., 2013). By and large, the greatest threat of mycotoxin contagion occurs while contaminated food product is utilized to make processed foodstuff or fodder for animals.

Some factors inflate yield loss owing to postharvest infection, viz., product type, cultivar vulnerability to postharvest disease, immediate environment (temperature, relative humidity and atmosphere composition), produce ripeness stage, methods used for disease control, produce management methods, postharvest sanitation. Postharvest infections are frequently categorized based on the initiation of fungal infection. The supposed dormant contaminations are those where the fungal pathogen begins contaminating the host typically prior to harvest, subsequently goes through a phase of rest and waits for the change in the physiological condition of the host alters in its support, and then the infection cycle starts. The remarkable physiological alterations that happen during the ripening of fruits/vegetables are usually the elicitors for reactivation of dormant contaminations. For instance, anthracnose disease in a range of tropical fruits is caused by *Colletotrichum* and *Botrytis cinerea* (Zakaria, 2021). In contrast, the other main cluster of postharvest infections is cropped up from those infections initiated throughout and after harvest. These infections frequently occur *via* surface injuries formed by motorized practice or pest attacks. These injuries are usually very minute and easily neglected during the handling of the harvested produce.

In these cases, *Penicillium* spp. and *Rhizopus stolonifer* are the most prevalent fungal pathogens which cause blue-green mould and transit rot, respectively. Besides these two, the banana crown rot fungus also takes this opportunity to enter the host tissue through these injuries and cause disease (Alvindia & Natsuaki, 2007).

3.1. Major sources of postharvest infection

Members of phylum Ascomycota and the allied Fungi Anamorphici (Fungi Imperfecti) are the major source of postharvest infections. The asexual phase of fungus Ascomycota, i.e., the anamorph, is typically found in many postharvest diseases of fungal origin than teleomorph, the sexual stage. Main fungal genera have an anamorphic phase because postharvest infections comprise *Alternaria*, *Aspergillus*, *Botrytis*, *Colletotrichum*, *Dothiorella*, *Fusarium*, *Geotrichum*, *Lasiodiplodia*, *Penicillium* and *Phomopsis*. However, few of these also exhibited their sexual stages (Santra et al., 2020).

Other vital genera as postharvest pathogens, belong to the phylum Oomycota such as Phytophthora and Pythium, cause several postharvest diseases, *viz.*, brown rot in the members of family Rutaceae (*Phytophthora citrophthora* and *P. parasitica*) while, Pythium spp. are known to cause a cottony leak of cucurbits. Likewise, phylum Zygomycota genera such as *Mucor* and *Rhizopus* are the primary postharvest pathogens Garcia et al. (2006) which can cause considerable post-harvest yield loss of the Solanaceous vegetables such as tomato and potato Table 1.

Table 1
Some common postharvest fungal infection (Santra et al., 2020).

Sr. No.	Fungal pathogen	Affected plant	Disease caused	Symptoms
1.	*Aspergillus niger* van Tieghem	*Allium cepa* L. (Onion)	Black mould	water soaked fleshy scale of bulb
2.	*Alternaria brassicola* (Schwein.) Wiltshire	*Brassica oleracea* L. (Cauliflower)	Early blight	Stem lesions and fruit rot
3.	*Alternaria solani* Sorauer	*Solanum lycopersicum* L. (Tomato)	Leaf spot	Concentric rings on fruit
4.	*Alternaria dauci* (J.G. Kühn) J.W. Groves & Skolko	*Capsicum annuum* L. (Chilli) & *Daucus carota* subsp. sativus (Hoffm.) Schübl. & G. Martens (Carrot)	Leaf blight	Lesions on leaf
5.	*Ascochyta pinodes* L.K. Jones	*Pisum sativum* L. (Pea)	Mycosphaerella blight	Shrinkage, the dark brown coloration of seeds
6.	*Botrytis cinerea* Pers.	*Solanum melongena* L. (Brinjal) & *Vitis vinifera* L. (Grape)	Gray mould rot Bunch rot/grey mould	Discoloration, water soaking, growth of grey tan mould on the affected area Fruit rots and drops off
7.	*Colletotrichum musae* (Berk. & M. A. Curtis) Arx.	*Musa* × *paradisiaca* L. (Banana)	Anthracnose	Black and brown spots on fruit
9.	*Erysiphe pisi* DC.	*Pisum sativum* L. (Pea)	Powdery mildew	White powdery spots on oldest leaves, pods
10.	*Fusarium solani* (Mart.) Sacc.	*Solanum tuberosum* L. (Potato)	Dry rot of potato	Tuber rot and shrivel
11.	*Fusarium equiseti* (Corda) Sacc.	*Brassica oleracea* L. (Cauliflower)	Fusarium wilt	Wilted leaves, brown stem, rot roots
12.	*Pythium* spp. Pringsheim	*Phaseolus vulgaris* L. (Beans)	Preemergence rot	Collapsed hypocotyls, water-soaked lesions
13.	*Peronospora viciae* (Berk.) Gäum.	*Pisum sativum* L. (Pea)	Downy mildew	Greenish yellow or brown blotches on the upper surface of the leaf
14.	*Phoma destructiva* Plowr.	*Solanum lycopersicum* L. (Tomato)	Phoma blight	Longitudinal oval lesions, grey-black spots on the stem
15.	*Penicillium digitatum* (Pers.) Sacc.	*Citrus limon* (L.) Osbeck (Lemon), *Citrus sinensis* (L.) Osbeck (sweet orange), *Citrus aurantiaca* (L.) Swingle (orange)	Green rot/ green mould	The water-soaked area on the peel, circular colony mould
16.	*Rhizopus stolonifer* Vuillemin	*Manilkara zapota* (L.) P. Royen (Sapota), & *Vitis vinifera* L. (Grape)	Soft rot	Water-soaked spots on the entire fruit
17.	*Verticillium theobromae* (Turconi) E.W. Mason & S. Hughes	*Musa L.* (Banana)	Cigar – end rot	Ash grey wrinkled lesions like burnt end of a cigar
18.	*Penicillium expansum* Link	*Malus domestica* Borkh (Red Apple) & Pyrus spp. (Pear)	Blue mold	Soft or watery decay of fruits
19.	*Alternaria alternata* (Fr.) Keissl.	*Carica papaya* L. (Papaya)	Anthracnose	Rotting of fruits
20.	*Botrytis cinerea* Pers. & *Colletotrichum* spp.	*Fragaria* × *ananassa* Duchesne (Strawberry)	Soft rot	Spoilage of fruits during storage

4. BIOLOGICAL CONTROL

Several reports regarding the biological control of postharvest fungal pathogens are available. Most of them are focused on the potential biological agents that are usually from the yeast group, such as the *Candida*, the bacterial cluster, viz., the species of *Bacillus* and *Pseudomonas*, and the fungal cluster, such as the species of genus *Trichoderma* that can colonize on the sites of infection and generate competition to the fungal pathogens (Liu et al., 2013). Undoubtedly, the impending biological control of postharvest fungal infections subsists, but the future accomplishment depends on the skill to achieve a reliable outcome in the field and after yield. Therefore, it is essential to augment the effectiveness of biological control agents by trying some unexplored organisms, such as bryophytes which have inbuilt antifungal efficacies and unique thallus organization (Carmona-Hernandez et al., 2019; Droby et al., 2009).

The available antagonists are effective within a range of pathogens and fruits and vegetables. They also require particular growth conditions, which are costly, and their shelf life is also problematic. Therefore, most antagonists usually fail to pacify all the required standards. In such a situation, the bryophytes can be used as natural fungicides more effectively than the available antagonists at low cost and a high level of reusability (Beneduzi et al., 2012; Nunes, 2012).

5. BRYOPHYTES AS NATURAL FUNGICIDES

Numerous compounds generated naturally by bryophytes have fungicidal possessions. The compound bibenzyls has proven very effective against a range of fungal strains. Besides this, several other natural compounds, viz., sesquiterpenoids, steroids, acetophenones, stilbenes, essential oils, etc., have been obtained from bryophytes exhibited to hold substantial antifungal action (Frahm, 2004). It is expected that these compounds of bryophytic origin would substitute the synthetic chemicals fungicides in the future if they were found to be safe for human beings and livestock. In that case, their possible noxiousness to consumers must be assessed aptly. However, there is no issue regarding the biodegradability of most of these compounds means that they are safe for the environment.

Recently, remarkable advancements in technology have done a lot in identifying and characterising phytochemicals of various species of bryophytes globally. The triggered production of various phytoconstituents via different stresses also support their utilities as antimicrobial potentials (Asakawa, 2004). Various types of flavonoids, terpenoids, alkanones, acetogeneins, fatty acids, bibenzyls, bisbenzyls, sterols and glycosides Table 2 have been extracted and evaluated from bryophytes (Asakawa et al., 2000; Ludwiczuk et al., 2009). Phytoconstituents extracted from bryophytes, bibenzyls and bisbibenzyls are among the essential phytochemicals having good inhibitory effects on the various fungal strains (Asakawa, 2004; Banerjee et al., 2000; Nandy & Dey, 2020). Among bryophytes, liverworts are habitually supplemented in lipophilic mono-, sesqui- and di-terpenoid content with characteristic bibenzyls and bis-bibenzyls. These compounds are monochromatic, solid ethane byproducts created through the flavonoid biosynthetic pathway.

Different sub-types of these compounds exist in diverse bryophyte species, viz., macrocyclic (*Asterella angusta* (Steph.) Pandé, K.P. Srivast. & Sultan Khan, *Blasia pusilla* L., *Dumortiera augustan* L.); cyclic (*Marchantia emarginata* Reinw., Blume & Nees); polychlorinated [*Riccardia polyclada* (Mitt.) Hässel]; hydroxybenzylated [*Radula complnata* (L.) Dumort.]; chlorinated [*Riccardia marginata* (Colenso) Pearson]; cinnamoylated (*Polytrichum pallidisetum* Funck); prenylated (*Radula perrottetii* Gottsche ex Steph.), and geranylated (*Radula kojana* Steph.) (Nandy & Dey, 2020). Amid all the classes and subclasses, marchantin category of macrocyclic bis-bibenzyls has been testified to hold sturdy bioactivities. Almost 70 macrocyclic and acyclic bis-bibenzyls have been isolated and chemically created to explicate their structural details and utility in various industries, including agriculture and horticultural uses (Asakawa et al., 2013, 2000).

6. POSTHARVEST FUNGI AND BRYOPHYTES

Bryophytes have been assessed for their antimicrobial potential extensively, and it has been verified that these miniature plants are an excellent source of bioactive metabolites and can be effectively used as an alternate source of unsafe fungicidal chemicals. As they grow in challenging habitats, they have very refined protective mechanisms against biotic and abiotic stress (including fungi.); they are the storehouse of diverse bioactive chemicals. Several species of liverworts and mosses are known to have antifungal efficacies due to their secondary metabolites, viz., terpenoids, bibenzyls, flavonoids, and fatty acids (Krzaczkowski et al., 2008). The antibiosis of many bryophytes has been assessed against several phytopathogenic fungi (Alam, 2012; Banerjee et al., 2000; Mohammed et al., 2005; S et al., 2009; Savaroglu et al., 2011; Singh et al., 2007). The phytoconstituents of bryophytic origin can cure the complications of predictable antibiotic confrontation by the fungal strains (Krzaczkowski et al., 2008). These bioactive molecules may be fungicidal or fungistatic, prying at cellular and genome levels obstructing metabolic pathways.

Usually, for the assessment of antifungal efficacies, the extracts were made with quite a few organic solvents or even water extractions and a combination of one or two organic solvents. Invariably ethanol, methanol, ether, chloroform, dimethyl sulfoxide (DMSO), chloroform, acetone, and hexane are the preferred choice for this purpose (Commisso et al., 2021). The thalli (gametophyte) and sporophytes of diverse bryophytes of different ages were taken and then surfaced before their crushing in the various solvents. The obtained solution was further used for in vitro experiments to assess their antifungals efficacies against the selected fungal pathogens (Alam et al., 2011). To date, several phytopathogenic fungi, *viz.*, (*Aspergillus niger* van Tieghem, *A. flavus* Link, *A. versicolor* (Vuillemin) Tiraboschi, *A. fumigatus* Fresenius, *Atheliarolfsii* (Curzi) C.C. Tu & Kimbr, *Alternaria alternata* (Fr.) Keissl., *Botryodiplodia theobromae* (Pat.) Griffon & Maubl., *Botrytis cinerea* Pers., *Fusarium moniliforme* Sheld., *F. oxysporum* Schlecht. f. sp. gladioli, *Penicillium funiculosum* Thom., *P. ochrochloron* Biourge, *P. funiculosum* Thom, *P. expansum* Link, *P. chrysogenum* Thom., *Rhizoctonia bataticola* (Taub.) Butl., R. solani J.G. Kühn, *Tilletia indica* Mitra, and *Trichoderma viride* Pers. have been reported to be moderately or entirely repressed by the extracts of *Atrichum undulatum* (Hedw.) P. Beauv., *Ctenidium molluscum* Mitt., *Dumortiera hirsuta* (Sw.) Nees, F*ontinalis antipyretica* Hedw., *Hypnum cupressiforme* Hedw., *Marchantia polymorpha* L., *Physcomitrella patens* (Hedw.) Bruch & Schimp., Plagiochasma appendiculatum Lehm. & Lindenb., *Rhodobryum ontariense* (Kindb.) Paris, and *Ptilidium pulcherrimum* (Weber) Vain (Deora & Suhalka, 2017; Dey & De, 2011; Sabovljevic et al., 2016; Veljic´ et al., 2010).

7. *SPHAGNUM*: THE MULTIPURPOSE MOSS

While numerous bryophytes have been shown to exhibit antifungal properties, their usage on a broad scale has been restricted due to species identification issues. Among all bryophytes, however, the easily identifiable moss, *Sphagnum*, has been extensively employed in cultivating several fruits and vegetables for a long time due to its ease of identification and collecting. This genus is commonly referred to as 'peat moss' in the horticultural sector and has shown significant promise for all-purpose applications. Not only is this moss suitable as a growing medium for many crops, but also it is an excellent packaging material for fruits and vegetables of economic value. Due to the abundance of biomass that may be utilised dry or

Table 2
Bryophytes and their Antifungal activity in different extracts

Bryophytes genera	Extractions	Antifungal against	Antifungal against
Atrichum undulatum, *Fontinalis antipyretica*, *Plagiothecium denticulatum*, *Pogonatum aloides*, *P. urnigerum*, *Polytrichum commune*, *P. formosum*, *Mnium hornum*, *Oligotrichum hercynicum*, *Scleropodium purum*, *Sphagnum fimbriatum*, *S. nemoreum*, *S. subsecundum*	Organic solvent extracts	*Botrytis allii*, *Fusarium bulbigenum*, *Pityriasis versicolor*, *Pyricularia oryzae*, *Rhizoctonia solani*	Savaroglu et al. (2011); Kerem et al. (2015)
Herbertus aduncus	A-Herbertenol, β-herbertenol, α-formylherbertenol, β-bromoherbertenol	*Botrytis cinerea*, *Rhizoctonia solani*	Glime (2017)
Bazzania trilobata	5- and 7-Hydroxycalamenenes, drimenol, drimenal, viridiflorol, gymnomitrol, bisbenzyls	*Botrytis cinerea*, *Cladosporium cucumerinum*, *Phytophthora infestans*, *Pyricularia oryzae*, *Septoria tritici*	Scher et al. (2004)
Balantiopsis cancellata	Trans-β-methylthioacrylate	*Cladosporium herbarum*	Labbe et al. (2005)
Pallavicinia lyellii, *Scapania verrucosa*	Ether, alcohol, and hexane extract	*Aspergillus niger*, *Fusarium oxysporum*, *Pyricularia oryzae*	Guo et al. (2008); Subhisha and Subramoniam (2006)
Anomodon attenuatus, *Dicranum scoparium*, *Homalothecium philippeanum*, *Hylocomium splendens*, *Leucobryum glaucum*, *Pleurozium schreberi*, *Palustriella commutata*, *Rhytidium rugosum*	Methanol and ethanol extracts	*Aspergillus niger*, *Penicillium ochrochloron*	Sabovljevic et al. (2016); Veljic´ et al. (2010)
Dumortiera hirsuta, *Plagiochasma appendiculatum*	Aqueous extracts	*Alternaria alternata*, *Aspergillus niger*, *Botrytis cinerea*, *Botryodiplodia theobromae*, *Fusarium oxysporum* f. sp. gladioli, *Penicillium expansum*, *P. chrysogenum*, *Trichoderma viride*	Alam et al. (2011); Deora and Suhalka (2017)
Bryum argenteum, *B. cellulare*, *Plagiochasma appendiculatum*, *Thuidium delicatulum*, *Ctenidium molluscum*, *Ptilidium pulcherrimum*, *Marchantia polymorpha*, *Hypnum cupressiforme*, *Fontinalis antipyretica var. pyretica*	Aqueous extracts	*Aspergillus niger*, *A. flavus*, *Penicillium funiculosum*, *P. ochrochloron*, *Rhizoctonia solani*, *Sclerotium rolfsii*, *Tilletiaindica*, *Trichoderma viride*	Deora and Suhalka (2017); Veljic´ et al. (2010)
Atrichum undulatum, *Marchantia polymorpha*, *Physcomitrella patens*, *Rhodobryum ontariense*	DMSO extracts	*Aspergillus versicolor*, *A. fumigatus*, *Penicillium funiculosum*, *P. ochrochloron*, *Trichoderma viride*	Sabovljevic et al. (2016)
Riccia gangetica, *Philonotis revoluta*	Acetone and methanol extracts	*Curvularia lunata*	Deora and Suhalka (2017)

rehydrated during and after postharvest activities, particularly in packing and transportation (Sambo et al., 2008). Chemical analyses of this moss have already explained its bioactive nature in its active form (Mandić et al., 2021). Since it is evident that even water extractions exhibited remarkable antifungal efficacies, they have been used in horticultural practices to protect the plant/plant's part from desiccation and microbial attack. *Sphagnum* is one of the best examples, which has been used in the horticulture industry as an indispensable part for an extended period (Glime, 2017).

Amazingly, this moss genus has excellent water absorption capacity and can slurp all available water and moisture in its vicinity at an incredible pace (Bengtsson et al., 2020). Therefore, dried thalli of *Sphagnum* can be used as stuffing material in paper cuttings and other synthetic materials during packaging and transportation. It will act as shock and moisture absorbers and diminish the fungal attacks in an eco-friendly and cost-effective manner. While, in wet form, its normal metabolism manufactures the bioactive compounds that will help constraint the fungi. Therefore, this moss can perform dual functions preventing fungal infections. Another critical aspect of *Sphagnum* and other mosses that is they are reusable and can be kept in a dry state for a long time in minimal space without any significant degradation in their thalli.

Likewise, many other bryophytes can protect fruits and vegetables after harvest from the fungal infestation due to injuries and unwanted water in the ambient surroundings.

8. DISCUSSION

Bryophytes have unique thallus organization and water relations. Hence these poikilohydric minutes plants are available for their cautious utilization in managing postharvest fungal diseases as a cost-effective and eco-friendly approach (Ghazanfar et al., 2016; Santra et al., 2020). Because of their resurrection nature, their storage and use have many benefits compared to synthetic fungicides, but they remained neglected (Drobnik & Stebel, 2018). The rehydrated thalli of bryophytes can generate many secondary metabolites that restrict surrounding pathogens' growth. The dried thalli can absorb all the unwanted water/moisture contents from the harvested produce if used either solely or in combination with packaging materials. Both the rehydrated and dried form are interconvertible. Thus, these thalli are ecologically remarkable regarding this unique property of water relations. A vast diversity of these plants is available for use in some new purposes apart from conventional horticulture uses. Huge biomass can also be grown either through tissue culture or from the spores, therefore the year-round availability. Apart from *Sphagnum* spp., now the other evaluated genera of bryophytes should be used in the horticulture industry as these valuable miniatured plants can assure top eco-friendly management of postharvest fungal attacks with minimum effort.

The extraction part of bryophytes needs further attention and inventiveness to increase the use of these plants at a large scale. Existing extraction methods are valuable and practical at the laboratory level, but a cost-effective approach is still required in the upcoming days for large-scale requirements. This is a challenge and opportunity for biochemists and bryologists.

9. CONCLUSION

Many fungal pathogens are the root cause of various postharvest diseases in economically important fruit and vegetables. Though, these strains can infect the fruits and vegetables before harvest and opt for a dormant period until the congenial environment during and post-harvesting of the produce for rapid growth and disease development. Usually, these fungal pathogens infect the yield through surface injuries. As a result, numerous bryophytes, particularly *Sphagnum*, can be employed throughout the harvesting process and afterwards to help prevent fungal infestations. Conventionally, synthetic fungicides have performed a dominant role in postharvest disease control. However, awareness regarding the hazardous nature of chemical fungicides in horticulture/agriculture is compelling the advancement of new approaches. In this scenario, the perspectives of bryophytes in control of many of the postharvest fungal borne diseases become imperative as a lucid, eco-friendly and cost-effective ploy.

10. FUTURE THRUSTS

The hunt for novel bioactive compounds of antimicrobial significance has been a significant concern for a long time. Recently, phytopathogenic contamination has hard up the horticulture and agricultural production constraints to an actual task. A range of plant extracts is used as biocontrol approaches in their basic and cleansed form. The prevailing synthetic fungicides face many problems, viz., drug resistance, nephrotoxicity, biomagnification, etc. In this regard, using extracts of these first land plants would provide a fresh, harmless, and the finest strategic tool in postharvest fungal control. The bryophytes are underexplored in their enigmatic phytochemistry and secondary metabolite production. The confidence is reliable on miniature green first land plants because they protect against fungal or bacterial attacks. Thus, the hunt is principally made on the vast bryo-diversity that contains remarkable potential as antifungal agents.

CONFLICTS OF INTEREST

The authors declare no competing interests.

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AUTHOR CONTRIBUTIONS

This work was collaboratively undertaken by all authors. AA conceived the subject. SJ and PB conducted the literature search and drafted the article. The final manuscript was reviewed and approved by all authors.

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