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REVIEW

Siberian plants: untapped repertoire of bioactive endosymbionts

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BACKGROUND: Endosymbionts are microorganisms present in all plant species, and constitute the subject of interest among the scientific community. These symbionts have gained considerable attention in recent years, owing to their emerging biological roles. Global challenges, such as antimicrobial resistance, treatment of infectious diseases such as HIV and tuberculosis, cancer, and many genetic disorders, exist. Endosymbionts can help address these challenges by secreting value-added bioactive compounds with various activities.
OBJECTIVE: Herein, we describe the importance of plants inhabiting Siberian niches. These plants are considered to be among the least studied organisms in the plant kingdom worldwide. Barcoding these plants can be of interest for exploring bioactive endosymbionts possessing myriad biological properties.
METHODS: A systematic survey of relevant scientific reports was conducted using the PubMed search engine. The reports were analyzed, and compiled to draft this review.
RESULTS: The literature survey on Siberian plants regarding endosymbionts included a few reports, since extremely few exploratory studies have been conducted on the plants in these regions. Studies on the endosymbionts of these plants are highly valuable, as they report potent endosymbionts possessing numerous biological properties. Based on these considerations, this review aims to create awareness among the global scientific community working on related areas.
CONCLUSION: This review could provide the basis for barcoding novel endosymbionts of Siberian plants and their ecological importance, which can be exploited in various sectors. The main purpose of this review is to create awareness of Siberian plants, which are among the least studied organisms in the plant kingdom, with respect to endosymbionts, among the scientific community.

Keywords endosymbiont, endophyte, siberian plant, bioactive metabolite, novel compound

Introduction

Medicinal plants constitute some of the important sources of medicines, with their phyto-compounds used in the preparation of most modern drugs (Newman and Cragg, 2015). The use of plant-derived products can be traced back to several millennia ago (Satish et al., 1999). Even currently, many plant extracts are used to prevent myriad human ailments, owing to their healing properties (Rather et al., 2016). Increase in scientific knowledge and development of modern pharmaceuticals in the past decades have caused considerable progress in the commercialization of plant-based therapeutics (Baker et al., 2015). Interestingly, plants are some of the most abundant living organisms occupying different ecological habitats worldwide (Baker et al., 2015). One such ecological habitat includes the geographical area covering Siberia, which is a vast region covering almost all of Northern Asia, sharing its border with different countries, such as, China, Kazakhstan, Mongolia, and other arctic regions (Raiklin, 2008). Apart from its vast territory, its varied climatic conditions, soil, and topography make Siberia an interesting habitat (Tchebakova et al., 2016). It can be considered that to date, Siberia is an "underexplored" area, with extremely few explorations carried out (Franke et al., 2004). The unique habitat constituted by the Siberian region supports abundant

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natural flora and fauna, which upon exploration, could be the natural repositories of diverse biological organisms. Since ancient times, local Siberians are reported to have explored the medicinal properties of plants for curing various ailments (Shikov et al., 2014). The traditional knowledge of these Siberian plants has been transferred from one generation to the next with intense focus on therapeutic effects and risk management. Most of these medicinal plants are regional, and are yet to gain global popularity. Based on these facts and considerations, this mini-review introduces the importance of Siberian plants and their untapped endosymbionts, which can help exploit their unique biological compounds having various activities.

Plants with biological activities inhabiting the Siberian region

To date, diverse Siberian plants have continued to serve as curative agents, employed by local Siberians using plant-based formulations. Scientific investigations of these herbal formulations are highly essential for barcoding the biological entities responsible for the activities. The flora of Siberian habitats is widely distributed in different biomes with rich diversity (Yashina et al., 2012). It is suggested that numerous Siberian plant species are known to be used in folk medicines, owing to their enormous potential in curing various ailments. Undoubtedly, these medicinal plants could be excellent sources of drugs; however, Siberian flora is one of the less explored subjects, with extremely few explorations carried out to date. Systematic surveys on the rich floral resource constituted by Siberian medicinal plants can open up new horizons. Certain studies have examined the biological properties of Siberian medicinal plants. For instance, *Bergenia crassifolia* (L.) is a popular traditional medicinal plant used in Siberia and other parts of Asia (Popov et al., 2005). It contains different bioactive phytocomponents with various biological activities, such as antimicrobial, antioxidant, cerebroprotective, hepatoprotective, and adaptogenic activities (Kokoska et al., 2002). This plant is well known, commonly as Siberian tea and Mongolian tea (Popov et al., 2005). Similarly, *Adonis vernalis* L. is a popular traditional medicinal plant observed in different parts of Russia. In Siberia, *Adonis vernalis* L. is used in treating heart and kidney disorders. Studies on *Adonis vernalis* L. have reported that flavonoids, phenolic compounds, and cardenolides are the major compounds present in the plant (Dragoeva et al., 2015). The Siberian plant, *Ledum palustre* L., known as marsh Labrador tea, is considered to have healing properties against arthrosis, cough, cold, leprosy, itch, insect bites, and sore throat (Kim and Nam, 2006). The use of *Atriplex halimus* is well-known, owing to its medicinal properties in curing stomach pain and chest and intestinal aliments (Chikhi et al., 2014). *Atriplex halimus*is considered as rich source of vitamins, tannins, flavonoids, saponins, resins, and alkaloids (Bayoumi and Shaer, 1992). *Rhodiola rosea* is a medicinal plant growing in crevices in mountain rocks and sea cliffs in the arctic region of Siberia (Marchev et al., 2016). It has a long history of use in traditional medicine. The phytochemicals in this plant include sterols, essential oils, phenolic compounds, waxes, proteins, and tannins (Panossian et al., 2010). *Rhodiola rosea*is reported to have adaptogenic activities, such as cardioprotective, neuroprotective, central nervous system-stimulatory, antidepressant, anti-fatigue, and nootropic activities (Alm, 2004). Similarly, the use of *Rhaponticum carthamoides,*with its adaptogenic properties, is well documented in the Siberian region (Lotocka and Geszprych, 2004). It is additionally used as a dietary supplement to promote muscle growth (Kokoska and Janovska, 2009). The major compounds in *Rhaponticum carthamoides* are steroids and phenolic compounds (Opletal et al., 1997). The medicinal plant *Tussilago farfara* is a popular species among local Siberian healers, as it is widely used in treating cough and bronchial infections (Kokoska et al., 2002). Furthermore, studies have highlighted the antimicrobial, anti-inflammatory, and antioxidant properties of *T. farfara* (Xue et al., 2012). *Chelidonium majus* L. is a medicinal herb, whose roots are traditionally used, for a wide range of pharmacological activities, in treating oral infections, cancers, ulcers, bronchitis, asthma, and many other conditions (Maji and Banerji, 2015). Studies have revealed that different parts of this plant contain various phytocomponents, such as chelidonine, berberine, sanguinarine, and chelerythrine (Kokoska et al., 2002). The medicinal plant *Sanguisorba officinalis* used in treating pathological hemostasis, inflammation, and possesses antioxidant, antitumor, anti-HIV-1, and potent antimicrobial activities as well (Liang et al., 2013). Similarly, *Hedysarum theinum* is a medicinal herb used in traditional medicine by Siberian communities. It is reported to have anti-inflammatory, diuretic, and pain-relieving activities (Vdovitchenko et al., 2007). There are many plant species that are highly popular among local Siberian traditional healers, and most of them are yet to be fully analyzed. A problem concerning Siberian medicinal plants is their availability throughout the year. In most cases, owing to harsh climatic conditions, such as heavy snowfall, the majority of these medicinal plants are destroyed, and goes unused. Furthermore, few Siberian plants are reported to be endangered and regional, harvesting such species may pose an imbalance in plant diversity. Therefore, to address these critical issues, the scientific community has shifted its focus beyond the plant kingdom, and recently the isolation of endosymbionts inhibiting medicinal plants have become a subject of interest.

Endosymbionts

The definition of the term endosymbiont is broadened, based on the potential beneficial interaction of endosymbionts with their hosts (Partida-Martínez and Heil,2011). Essentially, an endosymbiont can be defined as a microbial assemblage or organism living within a healthy living organism, and forming imperceptible relationships with its host (Strobel and Daisy, 2003). The first endosymbiont was identified in *Lolium temulentum* (Darnel), stimulating interest among scientific researchers to explore different endosymbionts (Kusari et al., 2012). The relationship of plants with microorganisms has been discovered from fossilized stem and leaf tissues, clearly indicating that this relation has evolved ever since the first plant appeared on the earth (Schulz and Boyle 2006). There are different beneficial characteristics of endosymbionts which are constantly being explored (Fig. 1). Endosymbionts occur in both monocotyledonous and dicotyledonous plants, ranging from yews, oaks, pears to herbaceous plants, such as maize, tomato, rice, and so on (Baker et al., 2015). The ideal characteristics of a potential endosymbiont are illustrated in Fig. 2. Endosymbionts can have different forms and generally, they may be classified as fungal, bacterial, and actinomycetic endosymbionts (Kusari et al., 2012). To date, there is extensive scientific literature concerning about fungal endosymbionts. Furthermore, based on their isolation source, endosymbionts can be categorized as root, stem, and leaf endosymbionts (You et al., 2012). According to Rodriguez et al.(2009), endosymbionts can additionally be classified as class I endosymbionts, which are reported to increase host biomass, aid in increasing drought tolerance, and secrete chemicals that are toxic to animals and prevent plants from being eaten. Similarly, Class II endosymbionts are grouped based on their location of presence, such as above-or belowground level, indicating that they are spatially distributed in different parts of host plants, and confer habitat-specific stress tolerance to host plants. Class III endosymbionts are classified based on their site of occurrence in aboveground tissues, and these endosymbionts are highly localized, including hyperdiverse fungal endosymbionts with endophytism with tropical trees, seedless vascular plants, and coniferous woody plants (Rodriguez et al., 2009).

Hosts and endosymbionts

The relationship between endosymbionts and plants is yet to be completely elucidated. Scientific studies have traced these interactions back to extremely early stages in evolution (Saikkonen et al., 2004). Endosymbionts form colonies within plants in both inter and intracellular regions, and migrate to other plant parts via vascular tissues (Gaiero et al., 2013). The magnitude and diversity of endosymbionts are influenced by the geographical area, nutritional conditions, biotic and abiotic factors (Hilarino et al., 2011). Tropical forests are considered some of the hotspots of structural

Figure 1 Endophytes (Endosymbionts) and their biological properties.

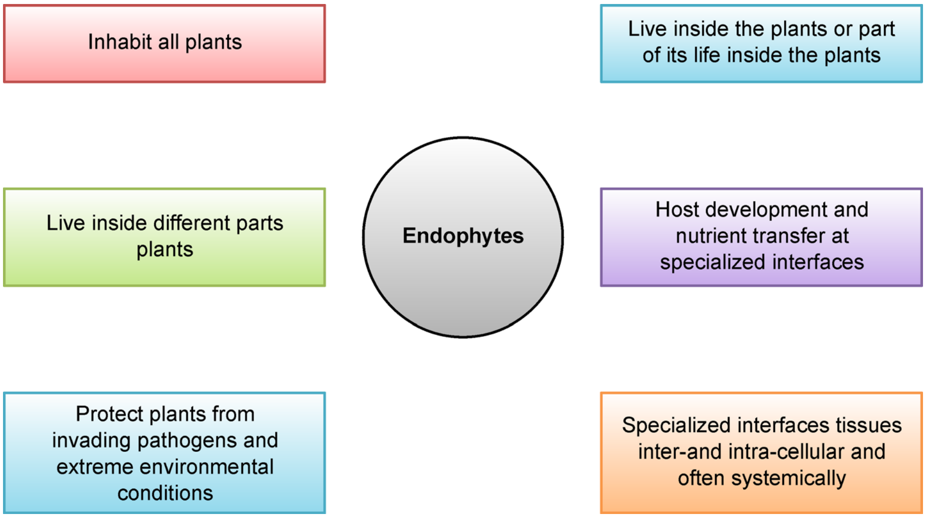


Figure 2 Characteristics of endophytes (endosymbionts).

diversity with a high density of endosymbionts, compared with dry forests (Arnold, 2005). Plants recruit endosymbionts from a large pool of microbial flora connected with the rhizosphere and phyllosphere, which enter and colonize different parts of plants (Compant et al., 2005). Additionally, studies have reported that changes in plant physiology influence the diversity of endosymbionts (Nair and Padmavathy, 2014). Endosymbiont transmission occurs both vertically, through seeds by vegetative propagation, and horizontally, via sexual and asexual sporulation (Zabalgogeazcoa, 2008). The physiologic and molecular mechanisms underlying the interactions between hosts and symbionts select mutualistic relationships rather than parasitic relationships (Xia et al. 2015). It is a cost-benefit-based interaction, which is reported to be harmless, gradually shifting toward a more specialized relationship actively involving both partners (Schulz and Boyle, 2006). This complex interaction overcomes physical and chemical barriers to minimize "balanced antagonism," which ensures the evasion of the host's defense mechanism by endosymbionts, their colonization within the host, and inhabitation without causing any visible or harmful effect (Schulz et al., 2015). According to the concept of balanced antagonism, there is a balance of virulence factors of the endosymbiont and defense mechanisms of the host plant to develop a nonpathogenic and asymptomatic relationship (Partida-Martínez and Heil, 2011). In the course of time, these relationships are influenced by external factors and physiologic conditions (Baker and Satish, 2012). In most cases, there is a genetic interaction resulting in plant gene modulation, which predicts the effects of endosymbionts on plants (Baker and Satish, 2012). Furthermore, the endosymbiont-plant co-evolution hypothesis suggests that possible gene clusters become homologous with symbionts, which influence plant defense mechanisms (Kusari et al., 2012). The defense mechanisms are triggered by the secretion of heterogeneous and homogenous bioactive compounds similar to those in the host, protecting the host against invasion by pathogens and insects, thus constituting an acquired immune system (Hardoim et al., 2015). Therefore, endosymbiont-plant interactions become more specific and stronger for their steady coexistence.

Endosymbiont isolation

Endosymbionts isolation is an important process conducted under strictly sterile conditions to eliminate contaminants, especially epiphytic flora (Kusari et al., 2012). The perusal of scientific literatures reveals different surface sterilization protocols involving the combined use of disinfectants, and some of the most used disinfectants are 2%–3.5% sodium hypochlorite, 0.01%–0.1% mercuric chloride, 50%–70% ethanol and 3% calcium hypochlorite (Strobel and Daisy, 2003). Furthermore, surface sterilization is coupled with the use of antibacterial and antifungal agents, depending on the endosymbiont type to be isolated (Baker and Satish, 2012). For instance, to isolate bacterial and actinomycetic endosymbionts, antifungal agents such as bavistin and cyclohexmide are widely used in surface sterilization, or incorporated into the media used for endosymbiont isolation (Baker and Satish, 2015). These agents suppress the growth of fungal species, and permit only bacterial endosymbionts to emerge from surface-sterilized plant parts. Similarly, to isolate fungal endosymbionts, different antibacterial agents are used to inhibit the growth of bacteria, permitting the emergence of only fungal endosymbionts. Interestingly, the microbiological media used for isolation additionally play a vital role. The majority of studies highlight the use of water agar for fungal endosymbiont isolation, and furthermore, nutrient agar is preferable for bacterial endosymbiont isolation. Apart from surface sterilization and isolation media, there are several factors influencing endosymbiont isolation, as described by Baker and Satish (2012). For instance, the selection of plant species can influence the endosymbiont type for isolation, as well. It would be of considerable interest to isolate potent endosymbionts from plants with a history of ethno-pharmocological use (Kusari et al., 2012). Moreover, the diversity of endosymbionts depends on the ecological biome of the plant and its geographical area (Baker et al., 2015). Evidence of potent endosymbionts in plants which are growing in habitats with harsh climatic conditions (Rodriguez et al., 2009). These physical factors influence plants, and have greater impacts on the diversity of endosymbionts in the plants as well (Kusari et al., 2012). Interestingly, the plant part selected influences endosymbiont isolation as well; for instance, endosymbionts isolated from roots are influenced by the rhizosphere (Baker et al., 2015).Younger plant tissues have been reported to be more suitable for endosymbiont isolation than older tissues (Kusari et al., 2012).

Biological properties of endosymbionts

The importance of endosymbionts as rich sources of bioactive metabolites can be demonstrated using the discovery of paclitaxel (Taxol), a highly valuable compound with anticancer activity (Strobel and Daisy, 2003; Newman and Cragg, 2015). Earlier, the only source of paclitaxel was the yew tree, and therefore, to isolate and commercialize paclitaxel, numerous yew trees were chopped, and paclitaxel was marketed; however research on endosymbiotic organisms resulted in considerable improvement, in secreting paclitaxel (Newman and Cragg, 2015). The secretion of secondary metabolites by endosymbionts could be related to independent evolution, which could result in the acquisition of genetic information from host plants, in turn enabling them to adapt within the plants (Farrar et al., 2014). Some of the most important secondary metabolites secreted by endosymbionts are shown in Fig. 3 and Table 1.

Endosymbionts as sources of antimicrobial metabolites

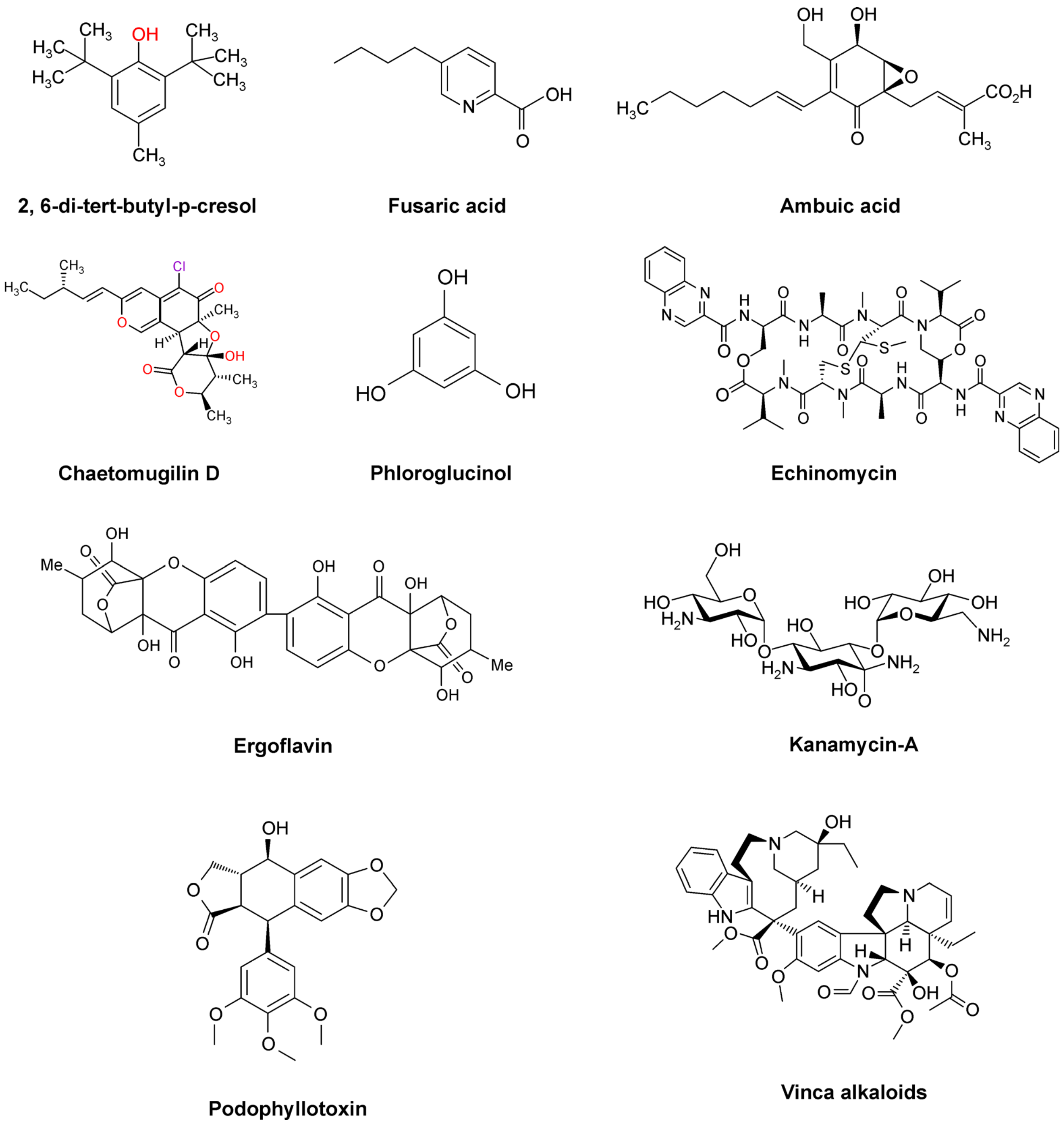
The rapid spread of drug-resistant microorganisms has caused the scientific community to develop novel strategies to combat multidrug-resistant pathogens. One such strategy includes the screening of diverse biological resources in the form of endosymbionts. Most endosymbionts are capable of secreting diverse classes of metabolites with antimicrobial activity, and a few relevant scientific reports are briefly discussed in the following sections.

Bacterial endosymbionts

Coronamycin, a novel metabolite, isolated from endophytic *Streptomyces* species, exhibits antifungal activity against human fungal pathogens and antimalarial activity against *Plasmodium falciparum* (Strobel et al., 2004). Similarly, p-aminocetophenonic acids, purified from endophytic *Streptomyces griseus,* isolated from *Kandelia candel,* show considerable antimicrobial activity (Guan et al., 2005). Similarly, kakadumycin A and echinomycin, purified from a *Streptomyces* endosymbiont, isolated from *Grevillea pteridifolia,* exhibits activity against gram-positive bacteria and antimalarial activity against *Plasmodium falciparum* (Castillo et al., 2002). The actinobacterium *Streptosporangium oxazolinicum,* isolated from orchids, and capable of producing spoxazomicins, exhibits anti-trypanosomal activity (Inahashi et al., 2011).The antibiotic 2, 4-diacetylphloroglucinol, was isolated from endosymbiotic *Pseudomonas fluorescens* Q2-87,was already reported to have great antimicrobial potential against an array of plant pathogens (Bangera and Thomashow, 1999).The novel metabolite Xiamycin A was reported to be secreted by the endosymbiotic *Streptomyces* sp strain GT2002/1503, isolated from the mangrove *Bruguiera gymnorrhiza* (Ding et al., 2010). The purified metabolite exhibits antibacterial activity against drug-resistant pathogens, including methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant *Enterococcus faecalis*. The number of bacterial endosymbionts is reported to be higher than that of fungal endosymbionts; however, the majority of studies on endosymbionts are related to the isolation of fungal species. In recent years, the identification of novel applications of

Table 1 Bioactive metabolites secreted from endosymbionts bearing biological potential

Endosymbionts	Host	Bioactive metabolite	Activity	References
Pseudomonas viridiflava	Grass	Ecomycins B & C	Antimicrobial	Miller et al., 1998
Chaetomium globosum	*Ginkgo biloba*	Chaetoglobosins A & C	Antimicrobial	Qin et al., 2009
Periconia sp.	*Taxus cuspidate*	Periconicins A & B	Antibacterial	Kim et al., 2004
Guignardia sp.	*Spondias mombin*	Guignardic acid	Antibacterial	Rodrigues-Heerklotz et al., 2001
Botryosphaeria rhodina	*Bidens pilosa*	Botryorhodines A-D	Antifungal	Randa et al., 2010
Streptomyces sp.	Monstera sp.	Coronamycin	Antifungal	Ezra et al., 2004
Cytonaema sp.	*Quercus* sp.	Cytonic acids A	Antiviral	Guo et al., 2000
Streptomyces NRRL 30562	*Kennedia nigriscans*	Munumbicin D	Anti malarial	Castillo et al., 2002
Streptomyces sp.	*Bruguiera Gymnorrhiza*	*Xiamycin*	Anti-HIV	Ding et al., 2010
Aspergillus niger. IFB-E003	*Cyndon dactylon*	Rubrofusarin B	Anti-tumor	Song et al., 2004



2, 6-di-tert-butyl-p-cresol

Fusaric acid

Ambuic acid

Chaetomugilin D

Phloroglucinol

Echinomycin

Ergoflavin

Kanamycin-A

Podophyllotoxin

Vinca alkaloids

Figure 3 Important Secondary metabolites secreted from endosymbionts.

bacterial endosymbionts has been of great interest.

Fungal endosymbionts

Fungal endosymbionts are considered rich sources of antimicrobial metabolites. Some of the important antimicrobial agents isolated from fungal endosymbionts include naphtho-gamma-pyrones, rubrofusarin B, asperpyrone B, aurasperone A, and fonsecinone, secreted by *Aspergillus niger* IFB-E003, an endosymbiont of *Cynodon dactylon* (Song et al., 2004). The endosymbiont *Chaetomium globosum,* isolated from *Ginkgo biloba,* secretes chaetomugilin D, which shows inhibitory activity against *Artemia salina* and *Mucor miehei* (Qin et al., 2009). The endosymbiont *Phoma sorghina,* isolated from *Tithonia diversifolia,* exhibits broad-spectrum antimicrobial activity against *Staphylococcus aureus, Escherichia coli,* and *Candida albicans* (Guimaraes et al., 2008). Endosymbiotic *Cryptosporiopsis* species secrete cryptocandin, which is proven to be an effective antifungal agent (Strobel et al., 2004) .Ambuic acid, a cyclohexenione derivative, is isolated from *Pestalotiopsis* and *Monochaetia* species related to many tropical plants, efficiently suppressing the growth of test fungal pathogens, thus acting as a potent antifungal agent (Li et al., 2001). Antiviral effects are achieved using cytonic acids A and B secreted by endophytic *Cytonaema* species (Guo et al., 2000). Similarly, *Penicillium chrysogenum,* isolated from unidentified tree leaves in Peru, exhibits anti-HIV-1 activity, by inhibiting the function of integrase, which is crucial for HIV replication, and the results are promising for the development of new lead compounds for antiretroviral therapy (Singh et al., 2003). Interestingly, endosymbiotic *Fusarium* species secrete fusaric acid, which exhibits potent anti-mycobacterial activity against *Mycobacterium bovis* BCG and *M. tuberculosis* H37Rv (Pan et al., 2011).

Antidiabetic activity

The screening of new antidiabetic drugs is a research topic of top priority in the scientific community, as a large fraction of the global population is affected by diabetes each year. Metabolites secreted by endosymbionts are reported to exhibit profound antidiabetic activity. In a study by Dompeipen et al.(2011), 45 endosymbionts from six medicinal plants in Indonesia were screened for α glycosidase-inhibitory activity. The results showed that seven endosymbionts could exhibit α glucosidase-inhibitory activity. Similarly, 17 fungal endosymbionts were isolated from *Salvadora oleoides* Decne, and were cultured further; their crude extracts were obtained using different solvents, and analyzed by performing glucose tolerance test on glucose-loaded fasted and alloxan-induced diabetic *wistar albino* rats (Abhijeet Singh, 2014). The results showed that four endophytic extracts reduced glucose levels. The compounds were purified for their identification, as 2, 6-di-tert-butyl-p-cresol and Phenol, 2,6-bis(1,1-dimethylethyl)-4-methyl (Dhankhar et al., 2013).

Anticancer activity

Novel anticancer drugs are constantly developed from natural resources, as most of the available chemically derived drugs and therapies have limitations. Endosymbionts secreting anticancer drugs can be identified, as the first endosymbiont observed to secrete Paclitaxel, a potent anticancer drug, was isolated from *Taxomyces andreanae* (Stierle et al., 1995). Similarly, the endophytic fungus *Entrophospora infrequens,* isolated from *Nothapodytes fetida,* can secrete camptothecin, a potent anticancer drug (Amna et al., 2006). In a study by Kharwar et al. (2008), 183 endophytic fungi were isolated from *Catharanthus roseus,* and screened for the production of anticancer compounds. The study revealed that *Alternaria* and *Fusarium oxysporum*can secrete Vinca alkaloids with anticancer activity. Furthermore, a study by Nadeem et al. (2012) reported that the anticancer drug podophyllotoxin is secreted by the endophytic fungus *Fusarium solani,* isolated from *Podophyllum hexandrum* roots. The endophytic fungus *Penicillium brasilianum,* isolated from *Melia azedarach,* can secrete phenylpropanoids, which are potent anticancer agents.

Anti-inflammatory activity

Inflammation is a vital process for maintaining homeostasis. The available anti-inflammatory drugs are not quite efficacious, and have various side effects. Hence, there is a great demand for new and safe anti-inflammatory drugs. Endosymbionts are reported to constitute one such source, as they can secrete potent and ideal anti-inflammatory compounds. Four different endosymbionts were isolated from *Loranthus,* and screened for anti-inflammatory activity (Govindappa et al., 2011)The results showed that *A.niger, Penicillum* species, and *Alternaria alternata* exhibit anti-inflammatory activity by inducing heat-induced albumin denaturation and stabilization of erythrocyte membrane. Furthermore, proteinase activity was inhibited, and BSA anti-denaturation and HRBC membrane stabilization assays indicated that endosymbiont extracts possess anti-inflammatory properties (Govindappa et al., 2011). Similarly, ergoflavin, isolated from an endophytic fungus in *Mimusops elengi* exhibits substantial anti-inflammatory activity (Deshmukh et al., 2009). Similarly, as expected, phloroglucinol, present in the crude extract of *Aspergillus fumigatus* secretions possesses anti-inflammatory property (Karmakar et al., 2013).

Endosymbionts as sources of biofuel

There is a serious issue concerning renewable energy sources. One relevant area of paramount importance is the extraction of biofuels from different natural resources. In addition to their bioactive compounds, endosymbionts can secrete compounds with potential for use as biofuel. The endosymbiont *Gliocladium roseum* (NRRL 50072), isolated from *Eucryphia cordifolia*, can synthesize a set of volatile hydrocarbons and their derivatives under microaerophillic conditions. This organism can secrete alkanes, undecanes, heptanes, octanes, and benzene (Stadler and Schulz, 2009). Similarly, the endosymbiont *Myrothecium inundatum,* isolated from *Acalypha indica* L., can produce several fuel-related hydrocarbons, such as octane, 1,4-cyclohexadiene, 1-ethylpropyl in culture under microaerophillic conditions (Banerjee et al., 2010).

Endosymbionts in agriculture

Agriculture is the mainstay of any nation; it is estimated that owing to pest infestation, numerous agricultural products are destroyed right from the period of seed sowing to product consumption. There are several means for controlling these pest infestations; however, the majority of methods involve the use of hazardous chemicals, including pesticides and fungicides. These chemicals have various limitations; they lead to biomagnification, and affect the natural environment and ecosystems. Recently, studies revealed the entry of pesticides into the human body and their detection in breast milk. Hence, there is a serious concern regarding the management of the agricultural sector. In recent years, the use of biological resources for pest biocontrol has gained considerable attention; plant-related microorganisms are employed in the management of plants, as these endosymbionts are reported to control pest infestation, and promote the growth and development of host plants, as well (Azevedo et al., 2000). These endosymbionts are responsible for developing induced systemic resistance (ISR), which is highly similar to systemic acquired resistance in plants. Moreover, studies reported that endosymbionts promote plant growth by cycling nutrients and minerals. They promote phosphate solubilization, indole acetic acid production, and siderophore production, and can supply vitamins to host plants. Additionally endosymbionts are involved in various beneficial processes, such as regulation of stomatal movement, modification of root morphology, and nitrogen metabolism. Recently, endosymbionts have been employed in the areas of forest regeneration and phyto-remediation of contaminated soils.

Future prospects of endosymbionts with respect to Siberian plants

The rich biodiversity of plants in Siberia is similar to a cornucopia for research on endosymbionts, based on the fact that a few reports are available on the plants growing in Siberia and surrounding geographical regions. Most of the plants are still being used by local Siberian healers, owing to their healing properties. Siberia constitutes an ecological niche with a huge geographical area and diverse climatic conditions, and the availability of plants in all seasons of the year is not plausible. The isolation of the compounds responsible for curative activities is not always possible, as most of the plants are endangered, and harvesting them may result in the loss of important flora; the plants may take several years to grow again, and some may not grow at all. Hence, to address these issues, identification of endosymbiotic microorganisms isolated from Siberian plants will be promising to reveal the diversity of chemicals secreted by these symbionts. As these symbionts are reported to be chemical synthesizers within plants, evaluation of these endosymbionts would be useful in exploring untapped microbial diversity, which could result in the discovery of novel endosymbionts that might be the first of their kind.

Conclusion

This review provides insight into the latest research on and emerging roles of endosymbionts for addressing global challenges, such as antimicrobial resistance and treatment of infectious diseases and genetic disorders, along with their influence on the agricultural sector. Furthermore, this review highlights the roles of endosymbionts as rich sources of biofuels. The main purpose of this review is to create awareness of Siberian plants, which are some of the least-studied organisms in the plant kingdom, with respect to endosymbionts, among the scientific community. Therefore, this review provides a wealth of information on different aspects and unexplored roles of endosymbionts.

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Compliance with ethics guidelines

Syed Baker, Svetlana V. Prudnikova and Tatiana Volova declare that they no conflict of interest. This manuscript is a review article and does not involve a research protocol requiring approval by the relevant institutional review board or ethics committee.

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