**Current Understanding of Bacterial Endophytes** **as an Enriched Source of Antibacterial Compounds**

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**Abstract:**

An exponential increase in population growth along with the alarming rise in bacterial infections invokes the need to find antimicrobial agents to tackle public health issues. Research to discover novel antibiotics against drug-resistant bacteria has become pivotal, especially after the emergence of the coronavirus pandemic. Previous reports have proved that several endophytic bacteria and fungi are found to produce various antibacterial compounds and secondary metabolites that can be treated against many resistant pathogenic microorganisms. The innocuous colonization of the endophytic bacteria inside the host and their ability to synthesize various beneficial compounds has led to various research to exploit them for medicinal applications. This review was compiled with the aim of focusing on the importance of endophytes as a source of antibacterial agents against bacteria of medical importance.

**I.**  **Introduction:**

Nature is a repository of abundant sources of novel drugs that are yet to be identified with therapeutic properties. Post the pandemic era there has been an exponential increase in the field of research which even led the scientific world to explore the realm of plants to develop a quick cure. After the Covid- 19 researchers have advanced in the field of omics to identify potential plant-derived molecules for drug discovery (Chojnacka et al. 2020). Several researches have been conducted to analyse the plant-derived polyphenols whose extracts are potent agents in coronavirus treatment and prevention (Singh et al. 2021). In the current review, we explore the potentiality of plant microbes, especially that of endophytic bacteria whose compounds might be potent antimicrobial agents that might help plants fight pathogenic microorganisms. Various reports prove that most of the plants studied to date have the presence of a myriad of endophytes thus proving the multifaceted relation between the host and microbe (Gouda et al. 2016). Endophytes are plant-colonizing microorganisms that reside in the internal tissues without causing any harm to the host (Kandel et al. 2017). The multifaceted association between the endophytes and the host has been demonstrated to be advantageous as most of them produce valuable compounds which have antimicrobial, antioxidant or antitumor properties (Wang et al.2014, Palem et al. 2015 Pan et al.2017). The endophytes yield various secondary metabolites that have antagonistic activity thereby defending the host from another pathogenic invasion (Shukla et al. 2014; Godstime et al. 2014).

 Fig**: 1. Endophytes a myriad source of antibacterial Compounds:**

**Antibacterial Compounds produced by the endophytes**-

* Secondary metabolites like tannins, flavonoids, saponins, coumarins, alkaloids, Phenols etc.
* Shikimic acids, ambuic acid, javacinin etc.



 **II.**   **Endophytes- A source of Antibacterial Compounds:**

Secondary metabolites play a pivotal role as defensive compounds that safeguard plants against pathogenic attacks (Divekar et al.2022).  Various favourable factors like ease of isolation, growth and minimal side effects on the environment have ameliorated microbes to be good sources of extraction for biologically active compounds that could have antimicrobial activity (Cowman 1999). Many plant secondary metabolites possess antimicrobial activity which includes phenolic and polyphenolic compounds, flavonoids, quinones, tannins, coumarins, terpenoids, diterpenoids,  alkaloids, lectins, polypeptides, polyketides and anthraquinones. (Savoia et al.2012, Upadhyay et al. 2014, Compean et al. 2013, Zheng et al.[2021](https://link.springer.com/article/10.1007/s11816-023-00824-x#ref-CR289)).Various scientists have stated the presence of azadirachtin in endophytic bacteria (Kharwar et al.2008). Over the years, it has been found that plants do not live independently but have co-evolved gradually with the microorganisms forming a consortium. This plant microbiome plays a protagonist in plant productivity, health and survival through the production of various antimicrobial compounds (Raaijmakers et al.2012). While exploring the realm of endophytes various scientists like Gunatilaka et al. (2006) explored that several compounds synthesized that the endophytes ha have antimicrobial properties and it has been appraised that these properties play a dominant role in the protection of the host plant from various pathogens, like bacteria, viruses, fungi, nematodes, etc. The endophyte-host consortium has empowered most of the endophytes (bacteria, fungi & actinomycetes) to play a substantial role in the production of bioactive compounds. Akter et al. 2022 worked on several medicinal plants to identify the potential endophytes that could produce plant-derived bioactive compounds which can be potent agents for drug innovation to cure SARS-COV-2.

**III.** **Antibacterial Compounds from Endophytic Fungus:**

In 2023, Singh et al. reported the presence of secondary metabolites from fungal endophytes and their ability to be exploited for novel drug production. Fadiji et al in 2020 reported that the endophyte *Alternaria* spp. showed satisfactory antibacterial activity against various pathogens and further studies led to the discovery of a novel alkaloid Altersetin which was isolated from the endophyte. They also reported the occurrence of fungal endophytes from *Artemisia annua* which have the ability to inhibit most phytopathogenic organisms due to the occurrence of n-butanol and ethyl acetate.

The studies put forward by Stierle et al. (1993) recognized the diterpenoid alkaloid taxol was the first secondary metabolite that was isolated from the endophytic fungus *Taxomyces andreanae* from the bark of *Taxus brevifolia*. Following these various studies have been conducted to identify the use of secondary metabolites of endophytic origin as alternate eco-friendly sources of antibacterial compounds.

Sharma et al. (2016) isolated the endophytic fungus *Pestalotiopsis neglecta* BAB-5510 from the gymnosperm *Cupressus torulosa,* which was found to be a rich source of phenols, flavonoids, terpenoids, alkaloids, tannins, carbohydrates and saponin. Reports put forward that crude extracts of the endophytic fungus *Pestalotiopsis*produced six novel compound ambuic acid derivatives and a new torreyanic acid analogue which was found to have the potentiality to inhabit the lichen *Multiclavula*  sp.(Ding et al.2009). Chen et al. (2016) concluded that the symbiotic association of the endophytic fungus *Gilmaniella* sp. AL12 with *Atractylodes lancea*led to the synthesis of several volatile oils such as β-caryophyllene, zingiberene, caryophyllene oxide, β-sesquiphellandrene, hinesol, β-eudesmol and atractylon which had played a significant role in antibacterial activity. Studies on root of herbal *Panax notoginseng* showed the presence of the endophyte *Trichoderma ovalisporum* strain PRE-5 and shikimic acid produced by the isolate was found to express activity against *S. aureus*, *Bacillus cereus*, *M. luteus* and *E. coli*. (Dang et al.2010). Bioactive compounds like Cycloepoxylactone and cycloepoxytriol were derived from the endophytic fungus *Phomopsis* sp. (internal strain no. 7233) of *Laurus azorica* which showed satisfactory antibacterial activity against *B. megaterium.*(Hussain et al. 2009 a). The endophytic fungus*Aspergillus sp. EJC08,*was reported to be isolated from the medical plant *Bauhinia guianensis .*Results showed the presence of the alkaloids, Fumigaclavine C and  Pseurotin A. Both Fumigaclavine C and Pseurotin A expressed antibacterial activity against *B.    subtilis, E. coli, P. aeruginosa, and S. aureus*. (Pinheiro et al. 2013) The bioactive compound Sclerotiorin was reported to show antibacterial activity against *S. aureus* ATCC 29213 which was due to the close association of the endophyte *Penicillium sclerotiorum* PSU-A13 with the host plant(Lucas et al. 2007; [Arunpanichlert et al. 2010](https://www.frontiersin.org/articles/10.3389/fmicb.2014.00715/full%22%20%5Cl%20%22B4)). Satisfactory antibacterial activity was reported from the endophytic fungus *Cytospora* sp. CR200 isolated from *Conocarpus erecta* . Reports conclude that the activity shown by the endophyte was due to the presence of Cytosporone D, E, and Cytoskyrin A. [Singh et al. (2007](https://www.frontiersin.org/articles/10.3389/fmicb.2014.00715/full#B120)).Various endophytic fungi isolated from different types of plants across the world were summarized (Deshmukh et al. 2015). Liu et al. (2008) reported the occurrence of several compounds like  7-amino- 4-methylcoumarin from the extracts of the endophytic fungus *Xylaria sp.* YX-28 isolated from G*inkgo biloba* L. Their works proved the existence of antibacterial activity against several food spoilage microorganisms such as *Escherechia coli, S. typhia, S. enteritidis, A. hydrophila, S. typhimurium Yersinia sp., V. anguillarum, Staphylococcus aureus, Shigella sp., V. parahaemolyticus, C. albicans, P. expansum, and A. niger*which were associated with the compounds synthesised by the endophytes. Several endophytes have been reported to produce chemical compounds that showed antibacterial activity as summarized in Table 1 and Table 2.

**Table 1: List of a few bioactive compounds isolated from endophytic fungi that shows antibacterial activity.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S.No.** | **Name of the host plants** | **Name of the endophytic fungi** | **Chemical compound Reported / Secondary metabolite** | **Reference** |
| 1. | *Azadirachta indica* A. Juss | *Chloridium* sp. | Javanicin | Kharwar et al. 2008 |
| 2. | *Ginkgo biloba* | *Xylaria* sp. YX28 | 7-amino-4- Methylcoumarin | Liu et al. 2008 |
| 3. | *Plumeria acutifolia* | *Phomopsis* sp. | Terpenoid | Nithya et al. 2010 |
| 4. | *Lichen Clavaroids* | *Pestalotiopsis* sp. | Ambuic AcidAmbuic acid derivative | Ding et al.,2009 |
| 5. | *Cupressus torulosa* | *Pestalotiopsis neglecta* BAB-5510 | Flavonoids, terpenoids, Phenols | Sharma et al.2016 |
| 6. | *Atractylodes lancea* | *Gilmaniella* sp. AL12 | β-caryophyllene, zingiberene, caryophyllene oxide, β-sesquiphellandrene, hinesol, β-eudesmol | Chen et al. 2016 |
| 7. | *Panax notoginseng*  | *Trichoderma ovalisporum*strain *PRE-5* | Shikimic acid | Dang et al. 2010 |
| 8. | *Laurus azorica* | *Phomopsis* sp. (internal strain no. 7233) | Cycloepoxylactone and cycloepoxytriol | Hussain et al.2009a |
| 9. | *Bauhinia guianensis .*  | *Aspergillus sp. EJC08,* | Alkaloids, Fumigaclavine C  Pseurotin A | [Pinheiro et al. 2013](https://www.frontiersin.org/articles/10.3389/fmicb.2014.00715/full#B101) |
| 10. |  *-* |  *Penicillium sclerotiorum PSU-A13* |  Sclerotiorin | Lucas et al. 2007;[Arunpanichlert et al. 2010](https://www.frontiersin.org/articles/10.3389/fmicb.2014.00715/full#B4)  |
| 11 | *Conocarpus erecta .*  | *Cytospora sp. CR200* | Cytosporone D , E , and Cytoskyrin A | [Singh et al. 2007](https://www.frontiersin.org/articles/10.3389/fmicb.2014.00715/full#B120) |
| 12. | *Ginkgo biloba* | *Xylaria sp. YX-28* | 7-amino- 4-methylcoumarin | Liu et al.2008 |

1. **Antibacterial Compounds from Endophytic Bacteria:**

Sing et al. (2017) were able to successfully prove the antibacterial activity of Silver nanoparticles (AgNPs) tested against human pathogens and deduced that the high antibacterial activity against Gram-positive and Gram-negative bacteria was due to AgNPs produced by the endophytes. It was reported that the extracts of *Coniothyrium sp*. isolated from the rhizomes of *Aralia nudicaulis*, contain palitantin, botrallin, craterellin C, mycosporulone, spiromassaritone, and massarigenin D thus exhibiting antibacterial activity (Li et al. 2015). Efomycin, Efomycin G, Oxohygrolidin, Abierixin and 29-O-methylabierixin were identified from endophytic isolates of *Streptomyces sp. BCC72023* from *Oryza sativa* (Supong et al. 2016). *Streptomyces sp. BO-07* was identified from *Boesenbergia rotunda (L.)* Mansf A. Igarashi et al.(2004) stated that the bioactive compound Coumarin from *Streptomyces sp. TP-A0556* isolated from *Aucuba Japonica* had antibacterial activity against several pathogens. Miller et al. (1998) mentioned the presence of *Pseudomonas viridiflava from Grass* and they concluded that the antibacterial activity showed by the isolates was due to the presence of Ecomycins B and C. Menpara et al. (2013) summarized data on endophytic bacteria isolated from different plants and the secondary metabolites produced by these endophytes with antimicrobial activity against plant and human pathogenic bacteria.

**Table 2: List of endophytes and their bioactive compounds isolated from endophytic Bacteria.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S.No.** | **Name of the host plants** | **Name of the endophytic bacteria** | **Chemical compound Reported / Secondary metabolite**  | **Reference** |
| **1.** | *Oryza sativa* L**.** | *Streptomyces sp. BCC72023* | Efomycin Efomycin G Oxohygrolidin Abierixin 29-O-methylabierixin | Supong et al. 2016 |
| **2.** | Grass | *Pseudomonas viridiflava* | Ecomycins B and C | Miller et al.1998 |
| **3.** | Boesenbergia rotunda (L.) Mansf A | *Streptomyces sp. BO-07* | 3′-hydroxy-5-methoxy-3,4-methylenedioxybiphenyl | Taechowisan et al. 2017 |
| **4.** | *Aucuba Japonica* | *Streptomyces sp. TP-A0556* | Coumarins | Igarashi et al. 2004 |
| **5.** | *Mahonia fortunei* | *Bacillus wiedmannii* | ergosterol derivative, 23*R*-hydroxy-(20*Z*,24*R*)-ergosta-4,6,8(14),20(22)-tetraen-3-one | Wang et al. 2019 |
| **6.** | *Tridax procumbens* L | *B. amyloliquefaciens, B. indicus, B. pumilus, B.subtilis).* | Flavonoids, Saponins | Praveena et al. 2013 |
| **7.** | *Calotropis procera* | *Bacillus siamensis* | Tannins, flavonoids, saponins,and phenolics | Hagaggai et al. 2020 |

1. **Conclusion and future perspectives:**

The alarming rise in the number of infections caused by drug-resistant pathogens has made scientists across the world explore novel antibiotics and their bioactive compounds at a fast pace so as to i) curb infections caused by drug-resistant bacteria ii) Increase occurrence of novel diseases caused by microorganisms ii) appearance of SARS- COVID -2 iii) widespread of several infectious diseases and the high mortality rate caused by infectious diseases like NIPAH and COVID 2 iv) Reappearance of infectious diseases and v) Unavailability of microorganisms targeted drug. Endophytes are a new area of the plant-microbe world that has been recently explored because of: a) synthesis of various bioactive compounds and secondary metabolites which can be harnessed to produce novel drugs b) New drug targets can be explored due to the resistant varieties that are being identified c) Fast growth rate d) Easy mode of culturing and studying e) Availability of nutrients f) better antibacterial and antibiotic sensitivity than plants g) Symbiotic and beneficial relation with plants h) They cause no or less side effects to the environment. The present review summarizes the various antibacterial compounds hidden in various endophytes and their association with different plants. This proves that endophytes are an area that can be still explored to harness these antibacterial compounds to develop novel drugs to treat various diseases across the world.

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