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The Study on the Promoting Effect of Rhizosphere Microorganisms on the Growth of Tissue-Cultured Ginseng and Its Mechanisms

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Abstract This study looks at how microbes around the roots affect the growth of tissue-cultured *Anoectochilus roxburghii* (also known as golden thread orchid). Some helpful bacteria, called PGPR, and certain fungi can make it easier for plants to use nutrients in the soil. As a result, the plants grow bigger and produce more ginsenosides, which are valuable compounds. A fungus called *Mortierella alpina* also helps by stopping harmful germs from spreading, which lowers the chance of disease and keeps the plant healthy. The study also tried mixing PGPR, good fungi, and organic fertilizer. This mix helped the plants grow better and reduced the need for chemical fertilizers, which is better for the soil and environment. In the future, researchers can study more about how these microbes and plants work together. This could help improve how we grow golden thread orchid and support more eco-friendly farming.
Keywords Rhizosphere microorganisms; *Anoectochilus roxburghii* tissue culture; Growth promotion; ginsenosides; Microbial inoculation

1 Introduction

Anoectochilus roxburghii is a kind of Chinese herbal medicine, which is widely used in traditional Chinese medicine, especially the ginseng type in tissue culture seedlings. It contains a variety of effective ingredients, such as ginsenosides, polysaccharides and peptides, which can resist oxidation, reduce inflammation and enhance immunity, so it is often used to treat diseases such as poor physical strength, loss of appetite and diabetes, and has been used in China for thousands of years (Xiang et al., 2008).

As both modern and traditional medicine continue to demand more *Anoectochilus roxburghii*, researchers have turned their attention to tissue culture as a way to boost production. This method allows plants to be grown under controlled lab conditions to produce key compounds such as saponins and polysaccharides (Wu and Zhong, 1999; Xu et al., 2023). Common approaches include callus culture, somatic embryogenesis, and cell suspension culture. Compared to traditional farming, these techniques are more efficient and easier to manage (Qiang et al., 2020; Xu et al., 2023). Conventional methods are time-consuming, labor-intensive, and often unstable (Wu and Zhong, 1999).

Extended periods of tissue culture may cause problems, such as chromosome instability or loss of cell differentiation ability, which can affect results (Liu et al., 2021). How to adjust the culture environment, formula and conditions so that plant cells can produce more needed metabolites is still the focus of attention (Jing, 2024; nhung et al., 2024).

This study explores a new approach: using rhizosphere microbes to promote the growth of tissue-cultured *A. roxburghii*. It focuses on how these microbes interact with the plant and how they can be used to improve the culture system. The goal is to raise both yield and active compound levels while addressing current problems in tissue culture, paving the way for more stable and sustainable production in the future.

2 Rhizosphere Microorganisms and Their Role in the Growth of Anoectochilus

2.1 Definition and classification of rhizosphere microorganisms

The soil area surrounding plant roots is called the rhizosphere, home to a large number of microorganisms, such as bacteria, fungi, and actinomycetes. These microorganisms help plants absorb nutrients, grow efficiently, and reduce disease. *Bacillus subtilis* and certain actinomycetes not only promote plant growth but also inhibit soil-borne pathogens (Dong et al., 2018; Ning et al., 2020).

Among fungi, arbuscular mycorrhizal fungi (AMF) and species from the Mortierella group can help plants absorb more nutrients and make them more resistant to drought or disease (Ning et al., 2020; Sun et al., 2022). Actinomycetes are long, thread-like bacteria that break down organic matter and release substances that fight germs (Wang et al., 2022).

Different environments and plant varieties will affect the composition of rhizosphere microorganisms. In the rhizosphere of *Anoectochilus roxburghii*, with the growth process, the species of bacteria will decrease, while the number of fungi will increase (Dong et al., 2018). This change is related to the amount of nutrients in soil, substances secreted by plant roots, and planting methods such as fertilization and shading (Sun et al., 2022; 2023; Wang et al., 2022).

2.2 The relationship between rhizosphere microorganisms and *A. roxburghii* and their impact on plant health

Rhizosphere microorganisms can interact with *Anoectochilus roxburghii*, which is very helpful for plant growth. AMF can form a symbiotic relationship with *Anoectochilus roxburghii* roots, especially when the soil is deficient in phosphorus, it can help it absorb more nutrients, promote root development, and make plants grow better during continuous cultivation (Ning et al., 2020). Beneficial bacteria such as *Bacillus subtilis* can inhibit the activities of pathogenic fungi such as *Fusarium*, reduce disease occurrence and improve plant survival rate (Dong et al., 2018; Dong and Li, 2024).

When AMF is applied as a biofertilizer, it increases the population of helpful microbes, improves nutrient availability, and lowers the risk of pathogen outbreaks (Ning et al., 2020). Root exudates from *A. roxburghii* also encourage the growth of beneficial fungi while limiting harmful ones, which enhances stress resistance and supports higher yields (Sun et al., 2023).

2.3 How rhizosphere microorganisms affect anoectochilus growth

Rhizosphere microorganisms can dissolve essential nutrients such as nitrogen, phosphorus, and potassium from the soil, aiding Anoectochilus in their absorption. For example, AMF hyphae can extend beyond the root zone, allowing the roots to absorb more nutrients (Ning et al., 2020). Some bacteria, such as Pseudoatrobacitra and Actinomycetes, can also improve ammonia and potassium utilization, significantly aiding nutrient absorption in *Anoectochilus roxburghii* (Ning et al., 2020). Using fertilizers with a balanced nitrogen, phosphorus, and potassium ratio can increase the number of beneficial fungi, thereby improving plant growth and ginsenoside content (Sun et al., 2022).

Some microorganisms can also secrete plant hormones, such as auxin, cytokinin and gibberellin. These hormones can stimulate root development and increase plant vitality. Hormones produced by microorganisms can also supplement the insufficient parts of plants, thus helping plants grow better (Wang et al., 2022). Some beneficial microorganisms can also regulate the hormone changes of plants in the face of drought or pest pressure, making plants more "resistant" (Ning et al., 2020).

These microorganisms can also inhibit the bacteria in the soil and protect *Anoectochilus roxburghii* by competing or producing antibacterial substances. *Bacillus subtilis* can significantly reduce the number of *Fusarium*, thereby reducing the plant disease rate and improving the health level (Dong et al., 2018; Ning et al., 2020). Biochar application can also improve the rhizosphere environment, allow beneficial microorganisms to form a more complex ecological network, and inhibit the growth of harmful fungi (Liu et al., 2019a; 2019b).

3 Rhizosphere Microorganisms Promote the Growth of Anoectochilus Tissue Culture Seedlings

3.1 Rhizosphere microorganisms significantly enhance the growth of anoectochilus tissue culture seedlings

After applying plant growth promoting rhizobacteria (PGPR) to *Anoectochilus roxburghii* tissue culture seedlings, the biomass of plants increased significantly, and some key nutrients in the soil became more abundant, which was conducive to the growth of roots and stems (Ji et al., 2018; fan et al., 2024). The root system of *Anoectochilus roxburghii* will secrete some substances, which will affect the species of microorganisms, making it easier for beneficial microorganisms to colonize around the root. This selective effect is helpful to increase the weight of roots and stems and the content of ginsenosides (Sun et al., 2023).

In practice, biochar addition is a relatively effective method. It can alter the structure of rhizosphere microorganisms and improve soil quality. This not only increases root weight but also reduces the incidence of some root diseases, making the plant appear healthier and grow faster (Liu et al., 2022a; Liu et al., 2022b).

3.2 Which microorganisms are useful for *A. roxburghii* and their role in tissue culture

Some microbes have shown clear benefits for *A. roxburghii*. For example, fungi from the Mortierella group are good at fighting off *Fusarium oxysporum*, a common plant disease. These fungi also help make phosphorus and other nutrients easier for the roots to take in, which is important for plant health (Wang et al., 2022).

Another helpful microbe is *Bacillus subtilis*, a common PGPR. It can make the plant taller, help roots grow longer, and increase ginsenoside content (Ji et al., 2018). Arbuscular Mycorrhizal Fungi (AMF) are also worth mentioning. When AMF are used in biofertilizers, they help the plant take in more nutrients and change the microbe population around the roots. This helps increase the number of good microbes and reduce harmful ones in the soil (Ning et al., 2020). These microbes can be added into the tissue culture system if used properly.

3.3 How microorganisms affect important growth indicators of *A. roxburghii*

Rhizosphere microorganisms can directly affect the root length, stem and leaf development and overall weight of *Anoectochilus roxburghii*. Bacteria such as PGPR can help the roots absorb nutrients faster by improving the availability of nutrients such as nitrogen and phosphorus in the soil, resulting in longer roots, thicker stems and stronger plants as a whole (Ji et al., 2018). These changes will also be reflected in the accumulation of ginsenosides, and the yield and quality will be improved.

The use of biochar has also had a positive impact. It can make the species of rhizosphere microorganisms more abundant and stable, so as to enhance the absorption function and disease resistance of roots. This is beneficial to cultivate healthier and higher yield *Anoectochilus roxburghii* plantlets (Liu et al., 2022a; Liu et al., 2022b).

4 Mechanisms Promoting the Growth of Anoectochilus

4.1 Nitrogen fixation and microbial enhancement of nutrient utilization efficiency

Rhizosphere microorganisms can transform nutrients in soil or air that plants cannot use into forms that *Anoectochilus roxburghii* can absorb. For example, some PGPR (plant growth promoting bacteria) can convert nitrogen in the air into nitrogen that *Anoectochilus roxburghii* can absorb, and release nutrients such as phosphorus and potassium, which are necessary for plant growth (PII et al., 2015; Hakim et al., 2021).

Another mechanism is called "rhizosphere priming effect" (RPE), which stimulates the decomposition of organic matter in soil by secreting some organic matter from plant roots. These decomposition processes can accelerate microbial metabolism and increase the formation of microbial residues, thereby improving the supply efficiency of nitrogen in soil (Pausch et al., 2024). The interaction between root exudates and microorganisms is the key to maintain soil nutrient cycle, which is very beneficial to the root growth of *Anoectochilus roxburghii*.

4.2 Microbial hormone production promotes the growth of anoectochilus

Beneficial bacteria in the rhizosphere can produce some hormones that promote plant growth, such as auxin and cytokinin. These hormones can make the roots of *Anoectochilus roxburghii* develop faster and have stronger absorption capacity, and promote the growth of stems and leaves (Ji et al., 2018; Hakim et al., 2021) (Figure 1).

Hormones like auxin stimulate root elongation, making it easier for plants to absorb nutrients from the soil. Cytokinins tend to make plant cells proliferate rapidly, which is very helpful for the development of stems and leaves.

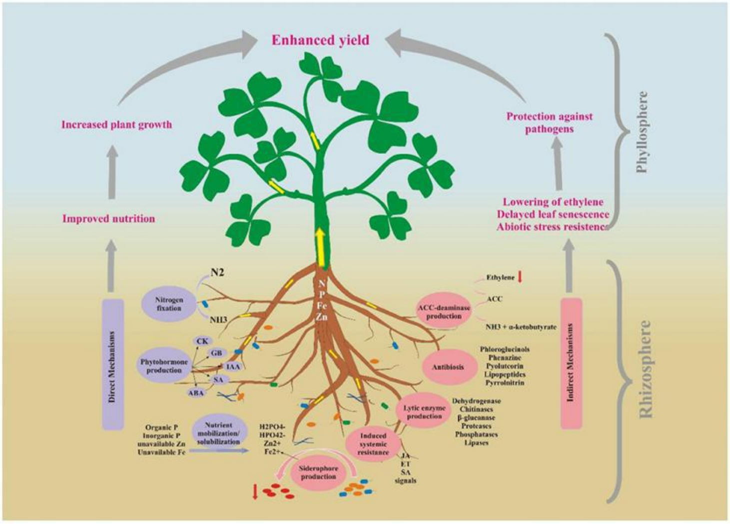

Figure 1 The benefits of PGPR-mediated rhizosphere engineering to the plant growth (Adopted from Hakim et al., 2021)

When some actinomycetes and other rhizosphere microorganisms are cultured together, they can also produce more plant hormones and some antibiotics. These substances can not only promote the growth of *Anoectochilus roxburghii*, but also enhance its resistance (Pausch et al., 2024). These studies showed that the reasonable introduction of these microorganisms into the cultivation system could create a more favorable environment for the growth of *Anoectochilus roxburghii*.

4.3 Microbial disease prevention: inhibiting pathogens and enhancing resistance

In addition to helping absorb nutrients and promote growth, some rhizosphere microorganisms can also play the role of "disease prevention". They can inhibit pathogenic microorganisms harmful to *Anoectochilus roxburghii*, especially *Fusarium*, which is easy to cause root rot. PGPR bacteria can produce some natural antibacterial substances, such as antibiotics, volatile organic compounds and iron carriers, to prevent the spread of bacteria in the soil (Dong et al., 2018; Kong and Liu, 2022). *Bacillus subtilis* is one of the good control bacteria, which has obvious effect on inhibiting *Fusarium oxysporum* (Dong et al., 2018).

The use of biological fertilizers containing AMF (arbuscular mycorrhizal fungi) can also reduce the number of harmful fungi in the soil and improve the rhizosphere microecology. This method can not only improve the disease resistance of *Anoectochilus roxburghii*, but also make the whole plant grow stronger and yield higher (Ning et al., 2020).

5 Application of Microbial Plant Interaction in Tissue Culture of *Anoectochilus roxburghii*

5.1 Difficulties in the application of rhizosphere microorganisms in *Anoectochilus roxburghii* tissue culture seedlings

To use rhizosphere microorganisms in *Anoectochilus roxburghii* tissue culture seedlings, the first problem is the composition of culture medium. The culture medium should not only meet the needs of plant growth, but also be suitable for the survival of microorganisms. But it is difficult to balance these two goals at the same time. Sometimes too many nutrients, such as nitrogen, phosphorus and potassium, will change the composition of rhizosphere microorganisms, and the species and quantity of fungi may also change (Sun et al., 2022).

The culture medium must also be clean and pollution-free. If pathogenic bacteria are mixed in, it will not only disrupt the original microbial balance, but also allow harmful bacteria to prevail and have adverse effects on *Anoectochilus roxburghii* (Zhang et al., 2023).

It is not easy to control environmental conditions. Temperature, humidity and light must be adjusted in place. A slight fluctuation may affect the activity of microorganisms. Sometimes when the environment changes, the beneficial bacteria may be reduced, but the harmful bacteria may become active (Wang et al., 2020). Microbial inoculation should be precise. For example, the inoculation location, dosage and time should be well controlled, otherwise beneficial bacteria are easy to be "squeezed out" by other bacteria in the soil (Wang et al., 2022).

5.2 Successfully inoculated microorganisms and their growth promoting effects

In the existing studies, some microorganisms have been successfully applied in *Anoectochilus roxburghii* tissue culture seedlings. For example, *Bacillus subtilis* can effectively inhibit *Fusarium*, a common pathogenic fungus, so as to make *Anoectochilus roxburghii* grow healthier (Dong et al., 2018). The method of inoculation can be seed wrapping, rhizosphere injection or soil root irrigation to directly send the bacteria around the plant roots (Wang et al., 2022).

In terms of effect, obvious changes can usually be seen after inoculation. Beneficial bacteria can not only improve the nutrient utilization rate, but also improve the soil structure, such as making the soil more loose and better water retention. *Mortierella alpina* was found to improve the availability of nitrogen and phosphorus in soil, and these two elements are very important for *Anoectochilus roxburghii* (Wang et al., 2022). Such microorganisms can also secrete plant hormones and other active substances to directly stimulate the growth of roots and stems (Hakim et al., 2022).

5.3 How the culture environment affects microbial activity and plant growth

The culture environment has a great influence on the growth of microorganisms and *Anoectochilus roxburghii*. If the temperature is too high or too low, and the humidity is insufficient, some microorganisms will lose activity, or even die. After microbial inactivation, rhizosphere ecology will also change, beneficial bacteria will decrease, and bacteria will easily spread (Wang et al., 2020).

Light is also a key factor. Plants grow by light cooperation. The more sufficient the light, the higher the photosynthetic efficiency of plants and the more energy they produce. These energies are not only supplied to themselves, but also released in the form of root exudates, further affecting the species and activities of root microorganisms (Sun et al., 2023) (Figure 2). Light intensity may also affect the synthesis of secondary metabolites such as ginsenosides in *Anoectochilus roxburghii*, which are the source of medicinal value of *Anoectochilus roxburghii* (Sun et al., 2022).

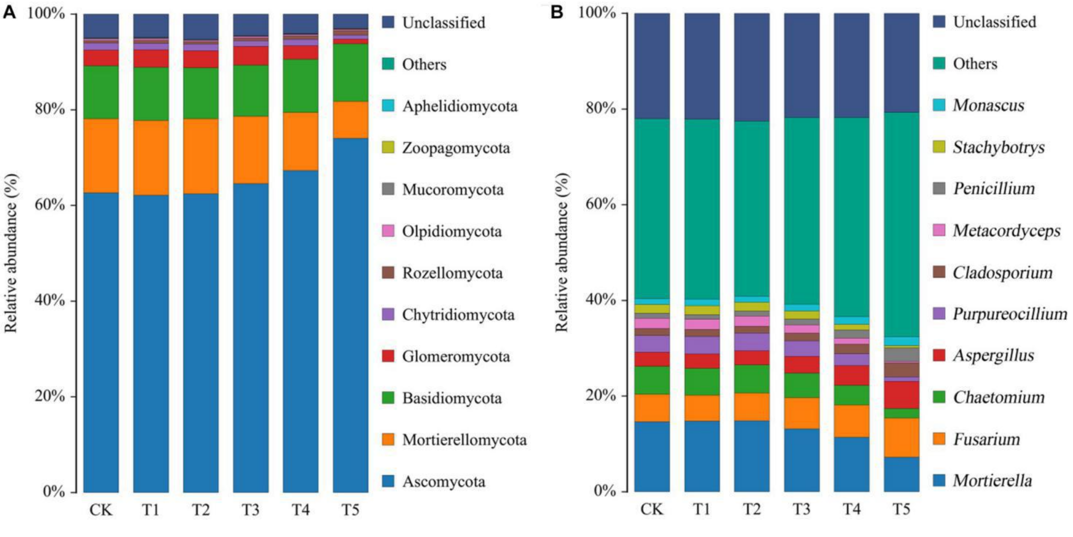

Figure 2 Relative abundances of fungal phyla (A) and genera (B) in the rhizosphere soil of ginseng under different root exudate concentrations (n = 3) (Adopted from Sun et al., 2023)

Image caption: Root exudate concentrations: CK, 0 mg·g^{-1}; T1: 0.3 mg·g^{-1}; T2: 1.5 mg·g^{-1}; T3: 3 mg·g^{-1}; T4: 6 mg·g^{-1};T5,15 mg·g^{-1} (Adopted from Sun et al., 2023)

6 Real-World Use of Rhizosphere Microbes in Growing *Anoectochilus roxburghii*

6.1 Using rhizosphere microbes to increase yield and support large-scale growing

Rhizosphere microbes can improve the balance of microbes in the soil and make nutrients more available. This helps *A. roxburghii* grow faster and stronger. Some PGPR (plant growth-promoting rhizobacteria) have been shown to increase plant biomass and raise ginsenoside levels, which is important for its medicinal use (Ji et al., 2018). These microbes help roots absorb more nutrients and also create a better environment around the roots (Kong and Liu, 2022; Liu and Gao, 2024).

Adding biochar during planting also works well. It helps increase the number of good microbes like fungi and bacteria while reducing the harmful ones. This makes the soil healthier and better for plant growth (Liu et al., 2022). This method not only boosts yield but also supports eco-friendly farming.

6.2 Using microbes in organic farming to reduce chemical fertilizers

In organic farming, chemical fertilizers can't be used, so rhizosphere microbes are a good alternative. Mixing PGPR with spent mushroom substrate (SMS) can improve enzyme activity and increase available nutrients in the soil, which leads to better growth and higher quality *A. roxburghii* (Fan et al., 2024).

AMF (arbuscular mycorrhizal fungi) also work well as biofertilizers. Over time, they help roots take in more nutrients and improve the microbe mix around the roots. This reduces the need for chemical fertilizers and fits well with organic farming practices (Ning et al., 2020).

6.3 Microbial inoculants for sustainable *A. roxburghii* cultivation

Some microbes can protect *A. roxburghii* from disease on their own. For example, *Mortierella alpina* helps fight soil-borne pathogens like *Fusarium*, which can cause root problems. It acts like a natural defense, helping plants stay healthy (Wang et al., 2022a).

These inoculants also increase the number of helpful microbes near the roots. That means better use of key nutrients like nitrogen and phosphorus, which supports long-term growth.

Combining NPK fertilizers with microbial inoculants can improve the effect even more. This mix helps good fungi grow better in the rhizosphere and keeps harmful microbes down. As a result, the plant becomes stronger and more resistant to stress (Sun et al., 2022). With proper nutrient planning and the right microbes, *A. roxburghii* can grow better, produce more, and be farmed in a way that's better for the environment.

7 Challenges and Limitations in Current Research

7.1 It's hard to find and identify the right microbes for *A. roxburghii*

Because there are many kinds of microorganisms around the root of *Anoectochilus roxburghii*, and they are constantly changing, it is not easy to find the bacteria that are really beneficial to plants. Factors such as planting years and planting methods of *Anoectochilus roxburghii* will affect the composition of rhizosphere microorganisms, which makes the research complicated (Xiao et al., 2015; Wang et al., 2020). Even though some studies have identified some common genera in *Anoectochilus roxburghii* rhizosphere, it is still unclear how these microorganisms work and whether there is a synergistic relationship between them (Dong et al., 2018; sun et al., 2023).

Not all microbes in the root zone are good. Some, like *Fusarium*, can cause disease. When trying to pick out useful microbes, there's a chance of choosing wrong—sometimes even encouraging harmful ones by mistake. For example, fungi like Mortierella can help the plant grow, but *Fusarium* often appears in the same environment and can harm it (Wang et al., 2022b; Sun et al., 2023). So, researchers need better tools to find the good ones while keeping the bad ones out.

7.2 No standard way to measure microbial effects

Right now, there's no one standard way to test how microbes affect *A. roxburghii*. Different studies use different methods—like high-throughput sequencing, PCR-DGGE, or BIOLOG systems. Each method has pros and cons, but they often give different or even conflicting results (Liu et al., 2022; Ning et al., 2022). On top of that, researchers use different soils, plant types, and growing conditions, which also change the outcomes.

Another problem is that there is no unified standard to evaluate the interaction effect of microorganisms and *Anoectochilus roxburghii*, such as how they affect plant health, yield and disease resistance. It is difficult to compare the results of different studies, and it is not easy to summarize a clear conclusion. Some studies focus more on the role of specific disease resistant strains (Dong et al., 2018), while others emphasize the functional changes of the overall microbial community (Wang et al., 2022). This divergence of research perspectives also hinders the in-depth understanding of the mechanism of rhizosphere microorganisms.

7.3 Hard to apply microbes in real-world growing conditions

There are also many problems in the use of microbial agents under different field conditions. A major problem is how to ensure that these bacteria can survive and play a role in a variety of soil and climate conditions. Environmental pressures such as soil pH, nutrient content, drought or high temperature can affect microbial activity, and even lead to inoculation failure (Liu et al., 2022; Ning et al., 2022).

Although biochar is a good material for soil improvement, its effect is also unstable. Under the field conditions of different types of biochar and different regions, the effect may be very different (Liu et al., 2022a; Liu et al., 2022b).

To really make microbial inoculants work in large-scale farming, we'd need better ways to manage what microbes go into the system. This means using high-precision tools, like microbial community regulation systems. But these tools are expensive and hard to apply widely right now (Wang et al., 2022; Huang et al., 2024). So while the lab results look promising, actually using these techniques in big plantations still faces a lot of technical hurdles.

8 Future Research Directions

8.1 Exploring the genetic and molecular basis of the relationship between anoectochilus and rhizosphere microbes

To further improve the cultivation efficiency of *Anoectochilus roxburghii*, it is necessary to understand how it interacts with rhizosphere microorganisms. Current studies have shown that this relationship is complex and may involve multiple genetic pathways and different levels of regulatory mechanisms (Huang et al., 2024a). There are many kinds of microorganisms around the root of *Anoectochilus roxburghii*, such as various bacteria and fungi. These microorganisms may affect the growth of plants through some specific genetic pathways (Xiao et al., 2015). In-depth study of these microorganisms, using methods such as genomic analysis, may reveal key genes or signaling molecules that may be the "switches" that promote nutrient absorption or disease resistance in Anoectochilus. Metagenomic techniques have also identified microorganisms, such as actinomycetes, that produce natural antimicrobial substances that help suppress harmful fungi in the soil (Huang et al., 2024b). Understanding the genetic basis of these mechanisms will facilitate the design of more precise microbial agents for efficient Anoectochilus cultivation in the future.

8.2 Improving the relationship between *A. roxburghii* and microbes using genomics and synthetic biology

Genomics and synthetic biology provide many new ideas for improving the coordination between *Anoectochilus roxburghii* and its rhizosphere microorganisms. Studies have found that some specific microbial communities can affect the growth status and disease resistance of *Anoectochilus roxburghii* (Fang et al., 2021; Huang et al., 2024b). If these microorganisms can be genetically modified by synthetic biology, it may enhance their ability to help plants absorb nutrients and inhibit bacteria.

This technology can also "Customize" the microbial community and match the strains specifically for the actual needs of *Anoectochilus roxburghii*. For example, by regulating the flora, beneficial bacteria can take advantage and reduce the number of harmful bacteria, so as to improve the yield and quality (Liu et al., 2022; sun et al., 2022). At the same time, microorganisms can also be allowed to produce some metabolites that are good for plants, such as stress resistant molecules or hormones, making *Anoectochilus roxburghii* more resistant to drought, disease and other adverse environments.

8.3 Developing novel microbial combinations or biofertilizers to improve cultivation results

In the future, efforts could be made to develop novel microbial communities or microbial-based fertilizers to improve the yield and quality of *A. roxburghii*. Current studies have shown that the use of soil amendments such as biochar can significantly impact the structure of rhizosphere microbes, improving soil conditions and promoting better *A. roxburghii* growth (Liu et al., 2022).

In this regard, plant growth promoting bacteria (PGPR) are a group of bacteria that deserve attention. If they can be combined with fertilizers, they can enhance the efficiency of nutrient transformation and promote root development (Pii et al., 2015). Microorganisms that can dissolve phosphorus or produce iron carriers can also help *Anoectochilus roxburghii* absorb key nutrients and improve the overall state of the plant. If these plans can be implemented in practice, it will not only improve the cultivation efficiency, but also make the planting process more environmentally friendly and sustainable.

9 Conclusion

Root microbes play an important role in helping *Anoectochilus roxburghii* grow, especially during tissue culture. Some helpful bacteria, like PGPR, can turn nutrients in the soil—such as phosphorus—into forms the plant can use. These bacteria also produce plant hormones like auxin, which help the roots grow better. As the roots develop, the whole plant gets stronger and makes more ginsenosides, which are the valuable medicinal compounds. Certain fungi, like *Mortierella alpina*, can also protect the plant by fighting off harmful pathogens like *Fusarium*, which causes root rot.

In practice, using PGPR or beneficial fungi as inoculants is an effective way to improve the yield and quality of *Anoectochilus roxburghii*. These microorganisms can improve the nutrient supply in soil, enhance plant disease resistance, and improve the stability of soil microbial community. If combined with AMF biological fertilizer, it can further promote nutrient absorption and alleviate the negative impact of long-term repeated cultivation on soil. Reasonable application of NPK fertilizer can also indirectly promote the activity of beneficial bacteria and enhance the adaptability of plants to environmental stress.

The connection between *A. roxburghii* and root microbes is about more than just helping the plant grow faster. These microbes can reduce the need for chemical fertilizers and pesticides, making farming more eco-friendly and efficient. But we still don’t fully understand how these microbes and plants work together. Future studies should look more closely at how these interactions happen at the genetic and ecological levels, especially under different growing conditions. This will help build better and more sustainable ways to grow *A. roxburghii*.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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