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Review Article

Microbial Interactions: A Case Study on Streptomyces

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Abstract:

Microbial interactions play a crucial role in the functioning and dynamics of ecosystems. These interactions encompass the complex associations among various microorganisms, such as bacteria, fungus, archaea, and viruses. Comprehending microbial interactions is essential for comprehending the intricacy of ecosystems, as well as for exploiting their potential in diverse domains, including agriculture, medicine, and biotechnology. This review provides a thorough examination of microbial interactions, including their various kinds, processes, ecological significance, and practical applications. Microbial interactions are essential in changing ecosystems and have substantial consequences for fields including agriculture, medicine, and biotechnology. Streptomyces, a group of thread-like bacteria, is renowned for its exceptional capacity to synthesise secondary metabolites with a wide range of biological properties. This review article seeks to investigate the complex microbial interactions involving Streptomyces and the consequences of these interactions on environmental and human well-being.

Key words: streptomyces; microbial interactions; antibiotics; symbiosis; quorum sensing; human health

Introduction

Microbial interactions encompass intricate exchanges of nutrients, signalling molecules, genetic material, and physical interactions among diverse microbes. Streptomyces, known for its abundant production of biologically active substances, has attracted significant interest due to its contribution to maintaining ecological balance and its promise in the field of pharmaceutical research [1]. Microbial interactions are essential for the functioning of ecosystems. Streptomyces, a bacterial genus, presents an intriguing opportunity to investigate microbial interactions [2]. Streptomyces species are renowned for their capacity to synthesise a diverse array of bioactive chemicals, notably antibiotics. An intriguing characteristic of Streptomyces is its function within the soil microbiome. The bacteria establish symbiotic associations with plants, facilitating nutrient acquisition and providing protection against diseases [1]. Streptomyces has the ability to synthesise antibiotics that hinder the growth of other microbes, so enhancing the survival of both the bacteria and the plants they interact with [3].

Streptomyces species not only interact with plants but also engage in intricate relationships with other microbes. Bacteria can establish mutualistic associations with fungus, such as mycorrhizal fungi, in which the bacteria supply nutrients to the fungi in return for organic molecules [1] [4]. Streptomyces can engage in resource competition with other bacteria in their surroundings by synthesising antimicrobial chemicals, so securing a competitive edge [2] [5].

Moreover, Streptomyces bacteria are capable of participating in cooperative contacts among individuals of the same species. Biofilms are frequently composed of intricate multicellular frameworks, in which many individuals collaborate to endure and flourish in demanding surroundings [6]. Biofilms have the ability to shield against environmental pressures and boost the synthesis of bioactive substances.

Investigating the interactions of Streptomyces bacteria can offer valuable knowledge on the ecology and evolution of microorganisms, as well as their potential uses in agriculture, medicine, and biotechnology[7]. Through comprehending these relationships, scientists can exploit the capabilities of Streptomyces and other bacteria for the creation of innovative antibiotics, biocontrol agents, and bioremediation tactics [7].

Microbial interactions can be categorised into several categories according to their results. Mutualistic interactions are cooperative connections in which two or more microorganisms derive benefits from their association [8]. Instances of this symbiotic relationship can be observed in nitrogen-fixing bacteria and leguminous plants, wherein bacteria supply nitrogen to plants in exchange for carbon molecules. Another illustration is the presence of mycorrhizal fungi, which augment the absorption of nutrients in plants [9].

In contrast, competitive interactions arise when microorganisms engage in a contest for scarce resources. This process can entail the synthesis of inhibitory substances, such as antibiotics or poisons, in order to acquire a competitive edge. Streptomyces, a bacterial genus, is well-known for its ability to produce antibiotics that hinder the growth of other germs [10].

Synergistic interactions refer to the collaborative efforts of diverse microorganisms to carry out intricate tasks that they are unable to accomplish on their own. For example, specific anaerobic bacteria collaborate to break down intricate organic substances in the gastrointestinal tract of animals [10].

Processes of Microbial contacts:

Microbial contacts can take place through different processes, such as direct physical contact between cells, the release of metabolites or signalling molecules, or the exchange of genetic material. Biofilm production is a prevalent strategy employed by microbial communities to offer physical protection and promote cooperation among microorganisms [11].

The ecological processes are heavily influenced by the crucial functions that microbial interactions play. They play a crucial role in the cycling of nutrients, breaking down organic matter and facilitating the recycling process [11]. This has a significant impact on the productivity and stability of ecosystems. Furthermore, the interactions between microorganisms have a significant impact on the health of plants and their ability to resist diseases, which in turn affects agricultural operations.

Utilisations in the fields of agriculture, medicine, and biotechnology:

Comprehending microbial interactions holds practical relevance in diverse sectors. Utilising mutualistic interactions in agriculture can boost crop yield and decrease reliance on chemically manufactured fertilizers [12]. Furthermore, the identification and examination of antimicrobial substances generated by microorganisms present promising strategies for addressing antibiotic resistance. Knowledge gained from studying microbial interactions plays a significant role in advancing probiotics, personalised medicine, and the identification of new bioactive substances that can be used for therapeutic purposes [13]. Microbial interactions can be harnessed for bioremediation purposes in order to clean up the environment.

Microbial interactions involving Streptomyces

1. Interactions of Streptomyces in Soil: Within soil ecosystems, Streptomyces engage in interactions with diverse microorganisms, encompassing other bacteria, fungi, and plants. These interactions might take the form of competition, cooperation, or symbiosis [14]. The interactions between Streptomyces and plants are particularly significant, as they have the power to impact plant development, disease resistance, and nutrient availability [14].

2. Antibiotic Production and Competition: Streptomyces species are well-known for their capacity to synthesise a wide range of antibiotics. These antimicrobial chemicals function as chemical weapons that aid Streptomyces in outperforming other microbes in the soil [15]. Furthermore, in the Streptomyces community, there might be rivalry for few resources, resulting in hostile interactions and the synthesis of antibiotics as a means of protection.

3. Synergistic Relationships: Although microbial communities are often characterised by competition, they can also exhibit synergistic relationships. Streptomyces can establish mutually advantageous symbiotic relationships with other microbes, such as mycorrhizal fungi and nitrogen-fixing bacteria, resulting in improved plant growth and nutrient uptake. These mutually beneficial connections emphasise the significance of collaboration in microbial communities [15].

4. Quorum Sensing and Communication: Microorganisms, such as Streptomyces, engage in communication by means of signalling molecules in a phenomenon known as quorum sensing. This communication facilitates synchronised actions, such as the simultaneous synthesis of enzymes or toxins, resulting in improved protection against rivals or cooperative interactions within microbial communities [16].

5. Human Health Implications: Streptomyces interactions have implications for human health that go beyond natural ecosystems. Medicine extensively utilises antibiotics generated from Streptomyces to effectively treat a range of infections [16]. Nevertheless, the appearance of antibiotic-resistant bacteria is a substantial obstacle. Gaining knowledge about the interactions between Streptomyces and human infections could offer useful insights into the creation of new drugs [16].

Identification of Streptomyces species and their interrelationships

Below are few instances of named Streptomyces species and their roles in microbial interactions:

1. Streptomyces coelicolor is a renowned species noted for its ability to produce a diverse range of secondary metabolites, including antibiotics like actinorhodin and undecylprodigiosin [17]. These antibiotics have the ability to impede the growth of other bacteria and influence the relationships between microorganisms in communities. Streptomyces coelicolor engages in communication and collaboration with its own species through a phenomena known as "bacterial warfare." This involves different strains competing or collaborating in the manufacture of antibiotics [17].

2. Streptomyces griseus is known for its ability to produce the antibiotic streptomycin, which has a wide range of antimicrobial effects [18]. Streptomycin possesses the ability to impede the proliferation of diverse bacteria, including those that are harmful. It serves as a valuable therapeutic agent for treating bacterial infections. Streptomyces griseus has the ability to hinder the growth of other microbes, hence influencing microbial interactions in different situations [18].

3. Streptomyces venezuelae is engaged in inter-specific interactions by secreting extracellular enzymes known as chitinases. Chitinases are enzymes that degrade chitin, a structural polymer present in the cell walls of fungi and arthropods [18]. Streptomyces venezuelae has the ability to break down the cell walls of other organisms or organisms it has a symbiotic relationship with by creating chitinases. This ability has an impact on the growth and survival of these organisms [18].

4. Streptomyces avermitilis is recognised for its ability to synthesise the avermectin class of antibiotics, particularly avermectin B1 and its related compounds. Avermectins are highly effective antiparasitic compounds utilised in veterinary medicine and agricultural contexts. They interfere with the neurological system of parasites, regulating their development and dissemination. Streptomyces avermitilis selectively affects certain parasites, hence influencing microbial interactions and contributing to the equilibrium of ecosystems [19].

Here are some selected instances of designated Streptomyces species and their functions in microbial interactions. It is important to mention that Streptomyces species display significant variation, and each individual strain may possess distinct antibacterial characteristics or interactions with other microorganisms [19]. The complex web of microbial interactions including Streptomyces plays a crucial role in shaping the dynamics and functionality of microbial communities.

Examples of the several modes of interaction between Streptomyces and microbes

Streptomyces is a group of thread-like bacteria that has significant significance in microbial communities because of its distinctive biological characteristics. Streptomyces can engage in several forms of interaction with other microbes, resulting in competitive, cooperative, or symbiotic partnerships. Here are precise instances of the various manners in which Streptomyces engages with microorganisms:

1. Antibiotic Production and Competition: Streptomyces is renowned for its capacity to synthesise a diverse array of antibiotics that possess the power to impede the proliferation of other microorganisms present in the soil. Streptomyces coelicolor, as an instance, generates the antibiotic actinorhodin, which hinders the proliferation of other bacteria. Streptomyces is able to produce antibiotics, which gives it an edge over other microbes and helps it maintain dominance in the soil. Nevertheless, certain bacteria have the ability to acquire resistance to certain antibiotics, resulting in the emergence of antibiotic-resistant strains [19].

2. Synergistic Relationships: Streptomyces can also establish advantageous symbiotic associations with other microbes, such as mycorrhizal fungi and nitrogen-fixing bacteria. Mycorrhizal fungi establish mutualistic symbiotic associations with plants, increasing their development and nutrient absorption by creating mycelia. Streptomyces can engage in interactions with mycorrhizal fungus, resulting in the generation of diffusible signalling molecules that enhance the growth of both Streptomyces and the fungi. In a similar manner, certain types of Streptomyces can engage in interactions with nitrogen-fixing bacteria, resulting in an increase in nitrogen fixation and the development of plants [19].

3. Quorum Sensing and Communication: Streptomyces possess the ability to engage in communication with other microorganisms through a mechanism known as quorum sensing. This process involves the use of signalling molecules as a means of communication between individuals within a population. Streptomyces griseus, a type of bacteria, creates a signalling molecule called A-factor. This molecule activates genes that are responsible for the creation of streptomycin, which is a significant antibiotic. Furthermore, quorum sensing enables Streptomyces to synchronise their actions with other microbes in the community, resulting in the simultaneous synthesis of enzymes or toxins, so enhancing their competitive edge [19].

4. Human Health Interactions: Streptomyces plays a significant role in human health by producing numerous antibiotics utilised in medicine. Streptomyces erythraeus is capable of producing the antibiotic erythromycin, which is employed in the treatment of many bacterial illnesses. Excessive utilisation of antibiotics has resulted in the development of bacteria that are resistant to antibiotics, emphasising the necessity for sustainable methods to manage bacterial illnesses. Gaining insight into the interplay between Streptomyces and other bacteria could facilitate the discovery of novel antibiotics or therapeutic approaches [20].

Advantages of the interactions of Streptomyces with other microorganisms to the field of microbiology.

1. Antibiotic Discovery: Streptomyces is well-known for its capacity to generate a diverse array of antibiotics. These chemicals have played a crucial role in the treatment of bacterial infections and have resulted in the preservation of several lives. An examination of the interactions between Streptomyces and other bacteria can facilitate the discovery of innovative antibiotics that possess distinctive mechanisms of action. Gaining a comprehension of these interactions can offer valuable knowledge about the genetic and metabolic pathways implicated in antibiotic synthesis, ultimately resulting in the identification of novel therapeutic candidates [20].

2. Ecological Understanding: The study of Streptomyces interactions enhances our comprehension of microbial ecology. Streptomyces is instrumental in influencing the composition of microbial communities in the soil and other habitats. Studying the dynamics of these interactions allows us to understand the intricate network of links between microorganisms and how they affect the functioning of ecosystems [20]. Understanding this knowledge is crucial for comprehending the wider ecological processes and functions of microbial communities.

3. Symbiotic Relationships: Streptomyces can establish mutualistic associations with other microorganisms, such as mycorrhizal fungi and nitrogen-fixing bacteria. These collaborations have substantial ramifications for the fields of agriculture and ecological restoration. Streptomyces has the ability to improve plant growth and increase nutrient uptake, which makes it a promising choice for use in agriculture. Gaining insight into the mechanics underlying these mutually beneficial relationships can aid in the advancement of environmentally friendly agriculture methods [21].

4. Biotechnological Applications: Streptomyces is not only very productive in synthesising antibiotics, but it also serves as a valuable source of many bioactive chemicals. Studying how it interacts with other bacteria can result in finding new natural substances that could be used in medicine, agriculture, and industry [21]. Enzymes and secondary metabolites generated from Streptomyces have several biotechnological uses, such as producing biofuels, acting as biocontrol agents, and aiding in bioremediation [21].

5. Genetic Manipulation: Streptomyces possesses intricate genetic mechanisms that regulate the synthesis of secondary metabolites. Examining the way it interacts with other bacteria can offer understanding of the regulatory processes implicated in antibiotic synthesis, resistance, and other significant characteristics [22]. This knowledge can be applied to control the genetics of Streptomyces, hence increasing production yields and expanding the variety of bioactive chemicals [22].

Antibiotics derived from the symbiotic relationship between streptomyces bacteria

Streptomyces bacteria have served as a significant reservoir of antibiotics, with multiple instances of antibiotic discovery resulting from interactions between Streptomyces and other microbes.

1. Streptomycin: Streptomycin is the initial antibiotic that was identified from Streptomyces. It was derived from Streptomyces griseus and exhibited efficacy against tuberculosis and other bacterial illnesses. Streptomycin has been important in fighting numerous diseases [22].

2. Tetracycline is a significant antibiotic that was identified from Streptomyces. The sample was obtained from the bacterium Streptomyces aureofaciens, which was kept separate from other organisms. Tetracycline

is a versatile antibiotic that effectively treats a diverse array of bacterial illnesses [22].

3. Erythromycin is a bactericidal antibiotic that is synthesised by the bacterium Streptomyces erythraeus. It is classified as a macrolide antibiotic and is capable of treating a range of respiratory tract and skin infections. Erythromycin is frequently employed as a substitute for penicillin [23].

4. Vancomycin is a powerful antibiotic that is mostly used to treat serious bacterial infections caused by Gram-positive bacteria, such as methicillin-resistant Staphylococcus aureus (MRSA). Streptomyces orientalis is the producer of this medicine, which has played a crucial role in the treatment of diseases caused by bacteria that are resistant to antibiotics [23].

5. Neomycin is a type of antibiotic that is synthesised by certain species of Streptomyces, specifically Streptomyces fradiae. Topical use of this substance is frequently employed to prevent or cure bacterial infections. Neomycin is utilised in conjunction with other medications for oral or topical administration [23].

6. Kanamycin is an aminoglycoside antibiotic that is synthesised by Streptomyces kanamyceticus. It exhibits strong antibacterial properties and is primarily employed for treating illnesses caused by Gram-negative bacteria. Kanamycin is employed as a selectable marker in molecular biology investigations [23].

These are a limited selection of antibiotics that have been derived from the interactions between Streptomyces and other bacteria. Streptomyces remains a significant reservoir of diverse antibiotics, and current scientific investigations strive to uncover novel molecules with potential therapeutic uses.

Streptomyces bacteria adopt multiple techniques to connect with other microorganisms, resulting in a complex mechanism of action in microbial interactions. Streptomyces, known for their high production of bioactive chemicals, frequently employ secondary metabolites, including antibiotics, to establish their ecological niche and engage with other bacteria. Streptomyces employs several essential methods of action:

Mechanism of action of streptomyces in microbial interactions

1. Antibiotic Production: Streptomyces species are renowned for their ability to produce a vast array of antibiotics. These antibiotics serve as weapons against competing microorganisms in their environment. By inhibiting the growth of other microbes, Streptomyces gains a competitive advantage and ensures its survival in nutrient-rich environments [23]. Some well-known antibiotics produced by Streptomyces include streptomycin, tetracycline, and erythromycin.

2. Antagonistic Activity: Streptomyces can directly inhibit the growth of other microorganisms through the production of inhibitory compounds, including antimicrobial peptides, enzymes, and secondary metabolites. These antagonistic activities can prevent the colonization of potential pathogens or competing organisms, thereby protecting plants and other beneficial microorganisms [24].

3. Quorum Sensing Modulation: Quorum sensing is a communication system utilized by many microorganisms to coordinate their activities based on population density [24]. Some Streptomyces strains can interfere with the quorum sensing of other bacteria, disrupting their communication and inhibiting their growth or virulence. This interference can provide a competitive advantage to Streptomyces in mixed microbial communities [24].

4. Nutrient Competition: Streptomyces bacteria are efficient competitors for nutrients in their environment [25]. They can outcompete other microorganisms by efficiently utilizing available resources and acquiring essential nutrients. This nutrient competition mechanism allows Streptomyces to establish dominance and thrive in specific ecological niches [25].

5. Siderophore Production: Streptomyces has the ability to produce small molecules called siderophores that scavenge and solubilize iron from the environment [26]. By sequestering iron, Streptomyces can limit the availability of this essential nutrient for competing microorganisms. This strategy enables Streptomyces to gain a competitive edge, as many microorganisms rely on iron for growth and survival [26].

6. Biofilm Formation: Streptomyces can form complex multicellular structures called biofilms. Biofilms provide physical protection for bacteria and facilitate the exchange of genetic material. Within biofilms, Streptomyces can cooperate with other microorganisms, sharing resources and enhancing their collective survival and metabolic activities [26].

Quorum sensing mechanisms utilised by Streptomyces

The modes of action utilised by Streptomyces can differ based on the particular species, ambient conditions, and the microorganisms they come into contact with. The combined actions of these systems play a crucial role in the ecological triumph of Streptomyces in microbial communities, as well as their prospective uses in agriculture, medicine, and biotechnology [27].

Streptomyces bacteria utilise diverse strategies to disrupt quorum sensing in other bacteria. Quorum sensing is a mechanism employed by numerous microorganisms to synchronise their actions and regulate the expression of genes in response to the number of individuals in their population. Streptomyces can exert substantial influence on the microbial interactions within a community by interfering with quorum sensing. Streptomyces disrupts quorum sensing and this disruption holds great importance [27].

1. Enzymatic Degradation: Certain Streptomyces species possess enzymes capable of breaking down the signalling molecules, also known as autoinducers, that participate in quorum sensing. Streptomyces interrupts the communication network of other bacteria by breaking down these molecules, which in turn prevents the activation of genes regulated by quorum sensing. This interference can impact the behaviour, pathogenicity, and biofilm development of other bacteria [27].

2. Signal Mimicry or Inhibition: Streptomyces is capable of synthesising compounds that imitate or hinder the activity of signalling molecules involved in quorum sensing [28]. These compounds have the ability to obstruct the attachment of autoinducers to their corresponding receptors in different bacteria, therefore interrupting the quorum sensing mechanism [28]. Streptomyces has the ability to control the behaviour of other bacteria and disrupt their coordination and communication by imitating or blocking their signals.

3. Streptomyces are renowned for their synthesis of many secondary metabolites, which encompass antibiotics. Certain metabolites have been discovered to disrupt quorum sensing in different bacteria [28]. For instance, some antibiotics synthesised by Streptomyces have the ability to regulate the generation and effectiveness of quorum sensing signals or interrupt the subsequent signalling pathways. This interference can impede the capacity of other bacteria to synchronise their behaviour and pathogenicity [29].

The importance of Streptomyces disrupting quorum sensing in relation to microbial relationships

1. Competition and Exclusion: Streptomyces can acquire a competitive edge by interfering with quorum sensing in rival bacteria [29]. This interference can hinder the proliferation and pathogenicity of other bacteria, hence creating opportunities for Streptomyces to colonise and thrive by accessing available nutrients. It enables Streptomyces to surpass other microbes and potentially prevent them from occupying particular niches or habitats [29].

2. Defence against Pathogens: Numerous pathogenic bacteria depend on quorum sensing to activate the production of harmful substances and the creation of biofilms [29]. Streptomyces has the ability to weaken the harmfulness of infections by disrupting quorum sensing, hence reducing their virulence towards the host or the surrounding environment. This interference can confer a defensive effect against infections and illness [30].

3. Altering Microbial Community Composition: Manipulating quorum sensing can disturb the equilibrium and fluctuations of microbial communities. Streptomyces has the ability to exert an influence on the growth and behaviour of other bacteria, hence impacting the makeup and structure of these communities [30]. This modulation can result in a series of interconnected consequences on ecosystem processes, the cycling of nutrients, and the overall functioning of microorganisms.

Comprehending the disruption caused by Streptomyces in quorum sensing offers valuable knowledge about their ecological functions and interactions within microbial communities. Furthermore, it emphasises the capacity of Streptomyces in the advancement of innovative approaches for biocontrol, disease prevention, and biotechnological applications.

The impact of Streptomyces' interference mechanisms on the production and maintenance of biofilms in other bacteria.

Biofilm production is an intricate and synchronised process that entails the proliferation and aggregation of microorganisms on various surfaces. Quorum sensing is a vital factor in the process of biofilm development, observed in both gram-negative and gram-positive bacteria. Streptomyces can greatly influence the creation and durability of biofilms in other bacteria by utilising interference mechanisms.

1. Signal synthesis disruption: Certain Streptomyces species produce enzymes capable of degrading the autoinducers responsible for quorum sensing. Streptomyces interrupts the communication network of other bacteria by breaking down these molecules, which in turn prevents the activation of genes regulated by quorum sensing that are necessary for the creation of biofilms [31].

2. Signal recognition inhibition: Streptomyces has the ability to generate compounds that hinder the binding of the signalling molecules involved in quorum sensing. Through the process of suppressing this recognition, Streptomyces has the ability to impede the activation of the genes regulated by quorum sensing that are necessary for the production of biofilms [31].

3. Antibacterial Compound Production: Streptomyces are renowned for their ability to synthesise a variety of secondary metabolites, which include antibiotics. Certain metabolites have been discovered to influence the process of biofilm formation in other bacteria. Streptomyces can disrupt the stability of bacteria by creating antibiotics like Actinomycin and Streptomycin, which inhibit the formation of biofilms [32].

4. Manipulating Microbial Community Composition: By interfering with quorum sensing, it is possible to disrupt the equilibrium and changes in microbial communities, thus controlling the production of biofilms. Streptomyces has the ability to exert an influence on the growth and behaviour of other bacteria, hence impacting the makeup and structure of these communities. As a result, it acts as a deterrent to the formation of biofilms [33].

The interference methods utilised by Streptomyces can have a substantial impact on the creation and durability of biofilms in other bacteria, consequently influencing the dynamics and functions of microbial communities. These mechanisms are innovative targets for the creation of new antimicrobial drugs and ways to disrupt biofilms.

Possible biotechnological uses

Streptomyces exhibits a diverse array of possible biotechnological uses owing to its distinct traits and interactions with other microbes. Below are a few illustrations:

1. Antibiotic Production: Streptomyces is renowned for its capacity to synthesise a wide range of antibiotics. These chemicals possess substantial therapeutic efficacy in the treatment of bacterial infections [34]. Through the examination of the interplay between Streptomyces and other microbes, we can discover previously unknown variations, detect innovative antibiotic substances, and enhance manufacturing methods [34]. This understanding has the potential to accelerate the progress of antibiotic development and address the escalating issue of antibiotic resistance.

2. Streptomyces is capable of producing a wide range of enzymes that have many applications in the field of biotechnology. These enzymes have use in various industries including food processing, medicines, biofuels, and bioremediation. Through comprehending the interplay between Streptomyces and other microbes, we may boost the efficiency of enzyme production, discover novel enzymes with distinct characteristics, and manipulate strains to achieve heightened enzyme output [35].

3. Lignocellulosic Biomass Conversion: Streptomyces have the ability to break down lignocellulosic biomass, which is an intricate combination of plant elements. The interactions between Streptomyces and other microorganisms, such as cellulolytic bacteria or fungi, might augment the efficacy of lignocellulosic biomass decomposition. This facilitates the advancement of more productive and economical methods for the manufacture of biofuels and biorefineries [36]. 4. Biocontrol: Streptomyces can serve as natural agents for controlling plant pathogens. Their antagonistic interactions with other microorganisms, such as fungi and bacteria, have the ability to inhibit the growth and dissemination of these pathogens. This presents opportunities for the advancement of eco-friendly biopesticides and biofungicides, thereby decreasing the dependence on chemical pesticides in the field of agriculture [37].

5. Bioremediation: Streptomyces possesses the capacity to break down a diverse array of pollutants, rendering it highly valuable in bioremediation endeavours. The interactions between this microorganism and other microorganisms, such as exchanging nutrients or cooperating in degradation processes, can improve the effectiveness of removing pollutants from polluted environments. Streptomyces-derived bioremediation techniques can be employed to mitigate the pollution of soil, water, and air [38].

6. Drug Discovery: Streptomyces synthesises numerous secondary metabolites, encompassing not only antibiotics but also anticancer compounds, immunosuppressants, and antifungal agents. Gaining insight

into the interactions between Streptomyces and other microorganisms can reveal previously unknown strains, innovative methods for producing secondary metabolites, and unique compounds with therapeutic properties. This can facilitate the exploration and advancement of novel pharmaceuticals and treatments [39].

The interactions between Streptomyces and other microorganisms are vital in the investigation and utilisation of its biotechnological capabilities. Through the analysis and comprehension of these interactions, we can uncover novel variations, enhance manufacturing methods, refine bioremediation and biocontrol tactics, and unveil previously untapped compounds and enzymes for diverse industrial purposes.

How the interactions of Streptomyces with other microorganisms can enhance the efficiency of bioremediation strategies for contaminated environments

1. Synergistic Degradation: Streptomyces have the capacity to break down a diverse array of pollutants, however it may not exhibit optimal efficiency when degrading all categories of toxins independently. Nevertheless, when engaging with other microorganisms, such as bacteria or fungi, a synergistic impact might occur. These bacteria may have mutually beneficial enzymes or metabolic pathways that collaborate to more efficiently degrade complicated contaminants. The collaborative behaviour can greatly improve the overall degrading efficiency of the bioremediation process [39] .

2. Nutrient Exchange: In polluted environments, the presence of nutrients may be scarce, which impacts the development and function of microorganisms engaged in bioremediation. Streptomyces, through its complex interactions with other bacteria, can enhance nutrition exchange by releasing and absorbing certain chemicals. Streptomyces enhances the survival and development of the entire microbial community by exchanging nutrients, resulting in a more effective bioremediation process [39].

3. Biofilm Formation: Streptomyces possesses the potential to create biofilms, which are intricate assemblages of microorganisms that attach to surfaces. Biofilms offer a sheltered habitat for microorganisms, enabling them to more effectively endure external pressures and amplify their metabolic functions. Streptomyces biofilms in bioremediation can form cooperative networks with other microbial species inside the biofilm [38]. This interaction allows for effective degradation of contaminants and improved removal of pollutants.

4. Genetic Transfer: Streptomyces exhibits a remarkable capacity for horizontal gene transfer, which involves the exchange of genetic material between distinct microbes [35]. This method facilitates the acquisition of novel genetic features, such as the capability to break down certain contaminants, from other microbes that exist in the surrounding environment. Streptomyces can boost its ability to clean up pollutants by exchanging genetic material with other microorganisms, acquiring advantageous genes that specifically target and break down toxins.

5. Detoxification and Metabolite Interactions: Streptomyces has the ability to generate secondary metabolites that exhibit detoxifying qualities or can impact the behaviour of other bacteria. Secondary metabolites possess the ability to inhibit the growth of detrimental or rival bacteria, enabling Streptomyces to establish dominance in the environment and enable the breakdown of pollutants. In addition, the metabolites generated by other microbes can stimulate or augment the metabolic processes of Streptomyces, hence increasing its bioremediation effectiveness [40].

The presence of Streptomyces in polluted environments can result in cooperative degradation, exchange of nutrients, formation of biofilms, transfer of genetic material, and interactions involving detoxification and metabolites. The interactions between microorganisms form a dynamic and cooperative microbial community, which greatly improves the effectiveness of bioremediation techniques. This allows for more efficient and sustainable solutions in the process of cleaning up polluted areas.

Use of Streptomyces in bioremediation strategies in real-world contaminated environments

Streptomyces has effectively been employed in diverse bioremediation approaches in actual polluted environments. Here are a few examples:

1. Polycyclic Aromatic Hydrocarbon (PAH) Contamination: PAHs are harmful and long-lasting pollutants found in soil and sediment. Scientists have effectively utilised Streptomyces spp. to address the issue of soils contaminated with polycyclic aromatic hydrocarbons (PAHs). This is possible due to the microorganisms' capability to generate biosurfactants, enzymes, and secondary metabolites that aid in the decomposition of PAHs [40]. An example of this is the bacteria Streptomyces griseus, which has been demonstrated to break down high-molecular-weight polycyclic aromatic hydrocarbons (PAHs), such as benzo[a]pyrene, in soil that is contaminated with waste from oil refineries [40].

Petroleum hydrocarbon contamination is a significant contributor to soil and water pollution. Scientists have employed Streptomyces spp. to clean up areas contaminated with petroleum by utilising their capacity to generate biosurfactants, enzymes, and secondary metabolites that aid in the breakdown of petroleum. An example of this is the bacteria Streptomyces VITS6, which has demonstrated efficient degradation of crude oil in polluted soil during laboratory experiments [41].

3. Pesticide contamination poses a significant risk to human health and the environment due to elevated amounts of pesticides in soil and water. Scientists have effectively utilised Streptomyces spp. to address the issue of pesticide pollution in certain locations [41]. This is made possible by harnessing their capacity to generate enzymes that aid in the breakdown of pesticides. An example of this is a research conducted in India where Streptomyces spp. were employed to restore soil that had been polluted with pesticides. The researchers discovered that Streptomyces spp. exhibited the capability to breakdown as much as 90% of pesticides within a 30-day period following the application of the bacteria [42].

4. Heavy Metal Contamination: The presence of heavy metals has been determined to present substantial hazards to both the environment and human well-being. Scientists have employed Streptomyces spp. to address heavy metal pollution in soil and water by utilising their capacity to generate biosorbents that can bind with heavy metals and aid in their extraction. An example of this is the bacterium Streptomyces sp. CATSI-2, which has demonstrated a high level of efficacy in the removal of lead and chromium from wastewater that has been contaminated [42].

Streptomyces has been effectively exploited in bioremediation procedures to address several types of environmental contamination, including PAHs, petroleum hydrocarbons, pesticides, and heavy metals. The bacteria's capacity to generate biosurfactants, enzymes, secondary metabolites, and biosorbents can aid in the breakdown and elimination of various pollutants, hence enabling more efficient and environmentally-friendly approaches to remediate contaminated settings [43].

Conclusion

In conclusion, microbial interactions are captivating and vital elements of ecosystems. The examination of microbial interactions offers useful insights into the complex connections that exist among microbes, their ecological functions, and their possible uses. Ongoing investigation of microbial interactions holds the potential to reveal unexplored areas in ecology, biotechnology, and human health, hence facilitating the development of sustainable and inventive solutions. The interactions between Streptomyces and other bacteria provide multiple benefits to the field of microbiology. They assist in the identification of new antibiotics, offer valuable knowledge on microbial ecology, and have potential uses in agriculture, biotechnology, and genetic engineering. Investigating these interactions enhances our comprehension of microbial systems and their pragmatic ramifications in diverse domains. Streptomyces engages in several interactions with microorganisms, such as resource competition, mutualistic connections, and communication via signalling molecules. These interactions can have significant consequences for both the environment and human well-being. Examining these interactions could yield valuable knowledge regarding the creation of new medications or sustainable methods for managing bacterial infections.

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