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Evaluating the Antibacterial, Anti-Inflammatory, And Immunostimulatory Potential of Streptomyces-Derived Bioactive Extracts

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Abstract

The increasing challenge of antimicrobial resistance has intensified interest in biologically derived compounds with antibacterial, inflammation-modulating, and immune-regulating properties. Members of the genus Streptomyces are promising sources of structurally diverse secondary metabolites, including compounds that may have pharmaceutical and biotechnology applications. This paper evaluates the potential of Streptomyces-derived bioactive extracts through a literature-based analytical approach integrating antimicrobial activity, anti-inflammatory potential, and immunostimulatory effects. The review draws on eight supplied references addressing actinomycete natural-product diversity, antioxidant activity in a mangrove-derived Streptomyces isolate, bacterial secondary-metabolite ecology, antibacterial mechanisms, antibiotic resistance, and immune responses in aquatic organisms. A proposed experimental framework is developed to assess extract composition, antibacterial efficacy, inflammatory responses, immune stimulation, and preliminary safety within a unified evaluation system. The synthesis indicates that the three biological activities should be examined independently before their combined therapeutic value is inferred. In particular, immune stimulation cannot automatically be interpreted as protection, and antioxidant activity does not independently establish anti-inflammatory efficacy. The principal contribution is an integrated assessment framework that links chemical characterization, functional testing, and safety evaluation while identifying the evidence required for reproducible validation. Further laboratory investigations are necessary to establish potency, selectivity, mechanism of action, and translational feasibility.

Keywords: Streptomyces; bioactive extracts; antibacterial activity; anti-inflammatory potential; immunostimulation; secondary metabolites; antimicrobial resistance; natural products; immune modulation.

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1. Introduction

1.1 Research problem and background

Antimicrobial resistance presents a continuing challenge for healthcare, veterinary medicine, and aquaculture. The reduced effectiveness of established antimicrobial agents creates a need to investigate alternative bioactive substances with different chemical structures and biological mechanisms. Talebi et al. (2019) discuss the broader crisis of antibiotic resistance, providing a rationale for investigating additional sources of antimicrobial candidates.

Among microbial natural-product producers, Streptomyces species are particularly relevant because actinomycetes can generate chemically diverse secondary metabolites. Research on marine rare actinomycetes emphasizes their potential as sources of structurally distinctive natural products, supporting further exploration of microbial biodiversity for bioactive compounds (Subramani &

Sipkema, 2019). The importance of this diversity is not limited to the discovery of new antibacterial substances. It also creates opportunities to identify compounds that influence oxidative processes, inflammatory pathways, or immune function.

Nevertheless, discovering biological activity is not equivalent to demonstrating therapeutic usefulness. A crude extract may contain several active and inactive constituents, and its observed effect may depend on concentration, extraction conditions, target organism, and assay environment. A substance that inhibits bacterial growth may also damage host cells, while a substance that stimulates immune activity may provoke excessive inflammation.

1.2 Research relevance and objectives

A central problem in evaluating Streptomyces-derived extracts is that antibacterial, anti-inflammatory, and immunostimulatory properties are often discussed as related benefits without sufficient evidence that they coexist in a single preparation or arise through compatible mechanisms.

The present paper addresses this problem through three objectives. First, it synthesizes the supplied literature to establish the scientific basis for investigating Streptomyces-derived bioactive extracts. Second, it proposes an integrated methodological framework for evaluating antibacterial activity, inflammation-related effects, immune stimulation, and preliminary safety. Third, it identifies the evidentiary requirements for progressing from initial screening to reproducible biological characterization.

1.3 Scope and significance

The analysis is limited to the eight references supplied by the user. It combines findings reported in those publications with a proposed research design; it does not claim to be a systematic review or a report of newly conducted experiments.

The principal significance lies in treating bioactivity as a multidimensional property rather than a single positive screening result. Such an approach may help researchers distinguish promising extracts from preparations that show activity under narrowly defined conditions but lack adequate selectivity, reproducibility, or biological compatibility.

2. Literature Review

2.1 Natural-product diversity and the potential of Streptomyces

Subramani and Sipkema (2019) identify marine rare actinomycetes as a promising source of structurally diverse natural products. Their review provides a foundation for investigating underexplored microbial groups and habitats, including environments that may contain organisms with distinctive biosynthetic capabilities. This perspective supports the broader proposition that microbial diversity can expand the pool of candidate bioactive substances.

However, natural-product diversity should be distinguished from demonstrated therapeutic efficacy. Chemical novelty does not necessarily imply strong antibacterial action, favorable pharmacological behavior, or low toxicity. Extracts must therefore be evaluated through both chemical characterization and biological testing.

Tan et al. (2018) investigated the antioxidative potential of Streptomyces sp. MUM292 isolated from mangrove soil. This study is relevant because antioxidant activity provides a possible starting point for investigating biological effects associated with oxidative stress. Nevertheless, antioxidant capacity alone cannot establish anti-inflammatory activity. Inflammation involves multiple cellular and molecular processes, and an extract may exhibit antioxidant effects without meaningfully altering inflammatory responses in a biological model.

The ecological perspective offered by Tyc et al. (2017) further illustrates that volatile and soluble secondary metabolites produced by soil bacteria can influence interactions within microbial communities. Such metabolites may have context-dependent functions, which cautions against assuming that their effects in ecological systems will translate directly into clinical applications.

2.2 Antibacterial activity and resistance-related considerations

The study by Wei et al. (2015) examines the antibacterial mode of action of 1,8-dihydroxy-anthraquinone from Porphyra haitanensis against Staphylococcus aureus. Although the compound is not presented as a Streptomyces-derived extract, the study provides a comparative example of why antibacterial research should examine mechanisms rather than relying exclusively on growth inhibition.

For Streptomyces-derived preparations, this distinction is important. An extract may suppress bacterial growth through effects on cell-envelope integrity, cellular metabolism, or other biological processes, but the actual mechanism must be established experimentally. Results from a compound obtained from another organism cannot be transferred directly to a different extract.

Talebi et al. (2019) frame antibiotic resistance as a major scientific and public-health concern. This context strengthens the rationale for screening new microbial products, but it does not establish that any particular extract will overcome existing resistance. Demonstrating such potential requires testing relevant bacterial isolates, determining susceptibility, and distinguishing growth inhibition from bacterial killing.

2.3 Immune regulation and biological context

Research on immune responses in aquatic organisms offers useful methodological considerations. Swain et al. (2007) investigated nonspecific immune parameters in brood Indian major carp, Labeo rohita, including seasonal variation. Their work illustrates that immune measurements can vary with physiological and environmental conditions. Consequently, immune-related assays require controlled experimental conditions and appropriate baselines.

Velázquez et al. (2017) reported a novel interferon-gamma homologue in Nile tilapia, Oreochromis niloticus, and linked it to immune responses in gills under different stimuli. This research underscores the importance of examining specific immune pathways rather than treating immune function as a single undifferentiated outcome.

Wangkaghart et al. (2021) examined immune responses and protective efficacy associated with two adjuvants administered alongside a Streptococcus agalactiae ghost vaccine in Nile tilapia. The distinction between immune response and protective efficacy is particularly important for the present topic: measurable immune activation does not necessarily establish improved resistance to infection.

2.4 Comparative synthesis and research gap

Taken together, the references provide complementary foundations: Subramani and Sipkema (2019) address natural-product diversity; Tan et al. (2018) provide a Streptomyces-specific antioxidant example; Tyc et al. (2017) examine secondary metabolites in microbial ecology; Wei et al. (2015) offer a mechanistic antibacterial example; and the three aquatic-immunology studies demonstrate the importance of context-dependent immune measurements.

The central gap is that these references do not collectively establish that one Streptomyces extract possesses all three target activities—antibacterial, anti-inflammatory, and immunostimulatory—at effective and safe concentrations. Nor do they establish a common mechanism linking the activities. The present paper addresses this gap by proposing a unified assessment framework while preserving the distinction between evidence already reported and experiments still required.

3. Methodology

3.1 Research design and analytical framework

The study adopts a literature-based analytical design supported by a proposed experimental validation framework. These components serve different purposes: the literature synthesis identifies relevant scientific principles, whereas the proposed framework describes how the biological properties of Streptomyces-derived extracts could be tested in future laboratory work.

The framework contains five connected stages: extract preparation and chemical characterization, antibacterial screening, anti-inflammatory assessment, immunostimulatory evaluation, and integrated safety analysis. Each stage generates evidence for a separate biological dimension. The final assessment considers whether the observed activities are reproducible, biologically relevant, and compatible with one another.

This structure is grounded in the natural-product diversity discussed by Subramani and Sipkema (2019) and the Streptomyces-specific antioxidant investigation reported by Tan et al. (2018). It also incorporates the broader principle that metabolite activity depends on biological context, as illustrated by Tyc et al. (2017).

3.2 Selection and characterization of extracts

A proposed experimental investigation should begin with authenticated Streptomyces isolates obtained from documented sources. Each isolate should receive a unique identifier, and its taxonomic identity should be established using suitable microbiological and molecular methods. Collection location, cultivation conditions, medium composition, incubation parameters, and extraction procedures should be recorded to support reproducibility.

After cultivation, the resulting material may be separated into extracellular and cell-associated fractions, depending on the research question. Extraction conditions should be selected to recover relevant compounds without introducing unacceptable contamination or degradation. Solvent controls and appropriate process blanks are necessary because residual solvents and medium-derived substances can produce misleading biological effects.

Chemical characterization should precede claims about individual active compounds. Suitable analytical techniques

may include chromatographic profiling and mass spectrometry, with further structural analysis where justified. A reproducible chemical fingerprint would allow researchers to compare batches and investigate whether differences in biological activity correspond to changes in extract composition.

The initial screening stage should retain both chemically diverse extracts and reproducible candidates. Premature selection based on a single positive assay could eliminate extracts with complementary biological properties or prioritize preparations whose apparent activity results from nonspecific toxicity.

3.3 Antibacterial activity assessment

Antibacterial testing should determine whether an extract inhibits bacterial growth and whether the effect varies across target organisms. A panel may include representative Gram-positive and Gram-negative bacteria, with additional resistant isolates when appropriate and authorized.

Initial screening may use agar-based diffusion methods, but diffusion results should be interpreted cautiously because compounds differ in solubility and their ability to move through agar. Broth-based susceptibility testing can provide more directly comparable concentration-dependent measurements. Follow-up testing should distinguish growth inhibition from bactericidal activity, where the research objective requires that distinction.

Wei et al. (2015) provide a comparative rationale for examining antibacterial mechanisms, while Talebi et al. (2019) establish the broader relevance of antimicrobial resistance. Neither reference demonstrates that a particular Streptomyces extract will have the same mechanism or activity profile. Therefore, any proposed mechanism must be supported by extract-specific evidence.

Controls should include an appropriate reference antibacterial agent, an untreated growth control, a solvent control, and sterility controls. Independent biological replicates and predefined criteria for interpreting results are essential. Results should be reported using the actual tested concentrations, variability estimates, and assay conditions rather than qualitative labels such as “strong” or “excellent” activity alone.

3.4 Assessment of anti-inflammatory potential

Anti-inflammatory activity should be investigated separately from antioxidant capacity. The findings of Tan et al. (2018) justify considering oxidative-stress-related properties as one research dimension, but they do not independently prove suppression of inflammation.

A proposed cell-based assessment could use a validated inflammatory model with appropriate untreated, stimulated, vehicle, and reference-treatment controls. Relevant endpoints may include selected inflammatory mediators, changes in inflammatory gene expression, and indicators of cellular stress. Assay selection should depend on the intended application and the biological model.

Cell viability must be measured alongside inflammatory endpoints. A reduction in inflammatory mediator production is not persuasive evidence of therapeutic anti-inflammatory activity if it results from widespread cell death or impaired cellular function. Where possible, more than one independent endpoint should be used to distinguish a specific inflammation-modulating effect from nonspecific suppression.

The experimental interpretation should also recognize that inflammatory responses can be protective. An extract that suppresses inflammatory activity under one condition may interfere with necessary host defense under another. Consequently, the objective should be to characterize the direction, magnitude, and context of the response rather than assuming that greater suppression is always preferable.

3.5 Evaluation of immunostimulatory effects

Immunostimulatory activity should be defined through measurable changes in selected immune functions. Depending on the intended application, these may include immune-cell viability, phagocytic function, cytokine responses, or other validated indicators of innate or adaptive immune activity.

The studies by Swain et al. (2007), Velázquez et al. (2017), and Wangkaghart et al. (2021) provide useful conceptual guidance. They show why immune parameters, specific signaling responses, and protective outcomes should not be treated as interchangeable measures.

A proposed experimental design should use an appropriate biological model, baseline controls, and reference conditions. The choice of endpoints should be established before data collection to reduce selective interpretation. Where an aquatic application is intended, species-specific physiological conditions and relevant immune indicators may be necessary.

The assessment should distinguish transient immune activation from sustained functional improvement. Increased cytokine production, for example, may indicate activation but does not by itself demonstrate enhanced

protection against infection. A stronger claim would require additional evidence connecting the measured response with a relevant functional outcome.

3.6 Integrated safety and data analysis

The three activity domains should ultimately be examined alongside preliminary toxicity and selectivity. Extract concentrations that inhibit bacteria should be compared with concentrations affecting host-cell viability and inflammatory or immune endpoints. These comparisons help identify whether a useful biological effect occurs within a tolerable concentration range.

The analysis should include independent experimental replicates, appropriate statistical methods, and transparent reporting of uncertainty. Multiple comparisons should be handled appropriately, and any exclusions or missing observations should be documented. Chemical fingerprints should be compared with biological outcomes to identify candidate associations, while avoiding claims of causation without additional testing.

A staged decision process is recommended. Extracts with reproducible activity proceed to chemical and mechanistic characterization; candidates showing promising activity and preliminary safety may advance to more biologically relevant models. This framework supports systematic prioritization without presuming that any candidate has already satisfied these criteria.

4. Results

4.1 Evidence derived from the supplied literature

The literature synthesis identifies three major areas of relevance: the availability of chemically diverse microbial products, the need for mechanism-oriented antibacterial investigation, and the context-dependent nature of immune responses. These areas provide a scientific basis for investigating Streptomyces-derived extracts, but the evidence does not establish a single preparation with all the biological properties specified in the title.

First, natural-product diversity provides a credible starting point for compound discovery. Subramani and Sipkema (2019) emphasize the potential of marine rare actinomycetes as sources of distinctive natural products. This supports the value of exploring underinvestigated microbial resources, although it does not establish the activity of every isolate or extract. Tan et al. (2018) provide a more specific example by investigating the antioxidant potential of a mangrove-derived Streptomyces isolate. The combined implication is that habitat-specific microbial diversity may offer useful candidates, but candidate selection requires direct testing.

Second, the antibacterial literature supports a distinction between activity screening and mechanistic validation. Wei et al. (2015) examined the antibacterial mode of action of a compound derived from Porphyra haitanensis. This provides a methodological example of mechanism-oriented analysis, rather than direct evidence for Streptomyces-derived substances. In parallel, Talebi et al. (2019) establish the relevance of the antibiotic-resistance problem. Together, these sources justify evaluating both antibacterial potency and the biological processes responsible for observed inhibition.

Third, the immune-related literature shows that biological responses depend on the organism and experimental context. Swain et al. (2007) investigated seasonal variation in nonspecific immune parameters in Labeo rohita. Velázquez et al. (2017) examined an interferon-gamma homologue and immune responses in Nile tilapia. Wangkaghart et al. (2021) considered immune response alongside protective efficacy in an adjuvant and vaccine context. Collectively, these studies support a multidimensional approach to immune assessment rather than the use of one indicator as a universal measure of immunostimulation.

4.2 Findings concerning the proposed assessment framework

The framework developed in this paper identifies five necessary components for evaluating the potential of Streptomyces-derived extracts: chemical characterization, antibacterial testing, anti-inflammatory assessment, immune-function evaluation, and safety analysis. These components address different sources of uncertainty and should be integrated only after their individual outcomes have been established.

Chemical characterization is necessary because an extract represents a mixture rather than a defined single compound. Without a chemical profile and appropriate batch controls, biological differences between preparations may be incorrectly attributed to a particular organism or mechanism. A stable chemical fingerprint would improve the interpretability of subsequent experiments.

Antibacterial testing should establish concentration-dependent activity against clearly identified organisms. The assessment should distinguish preliminary screening results from confirmed susceptibility and mechanistic evidence. An extract that produces an inhibition zone may warrant further

study, but such a result alone cannot demonstrate bactericidal action or efficacy against resistant infections.

Anti-inflammatory assessment requires evidence that inflammatory endpoints change under controlled conditions. Antioxidant activity may support a hypothesis for further testing, but it cannot substitute for direct measurements of inflammation-related responses. Viability controls are necessary to distinguish a specific effect from nonspecific cellular damage.

Immunostimulatory assessment requires a similarly careful distinction between activation and benefit. Changes in immune markers may provide useful mechanistic information, but functional relevance depends on the model and the endpoint. The aquatic-immunology references particularly illustrate the importance of physiological context and the distinction between immune response and protection.

Finally, safety assessment provides a necessary basis for integrating the three activity domains. A preparation cannot be considered a promising therapeutic candidate solely because it displays multiple biological effects. Those effects must occur at concentrations that are sufficiently selective and compatible with the intended application.

4.3 Interpretation and evidentiary boundaries

The main finding is therefore methodological rather than experimental: the supplied literature supports the rationale for evaluating Streptomyces-derived bioactive extracts through an integrated framework, but it does not establish their combined antibacterial, anti-inflammatory, and immunostimulatory efficacy.

No new inhibition measurements, inflammatory biomarker values, immune-response data, statistical tests, or toxicity results were available for this paper. Consequently, no experimental efficacy ranking or quantitative comparison among extracts can be reported. The proposed framework instead identifies the measurements needed to generate such findings in a future study.

This distinction is important for research quality. It prevents the general promise of microbial natural products from being converted into unsupported claims about a specific extract and provides a transparent route from literature-based rationale to experimentally verifiable conclusions.

5. Discussion

5.1 Biological potential and the importance of integrated evaluation

The literature supports investigating Streptomyces-derived bioactive extracts as candidate sources of biologically active compounds, but their value depends on the relationship between chemical composition, functional activity, and biological safety. Subramani and Sipkema (2019) highlight the importance of natural-product diversity in identifying potentially useful microbial metabolites. This perspective provides the theoretical foundation for examining diverse Streptomyces isolates rather than restricting investigations to organisms with previously established applications.

Nevertheless, diversity introduces an analytical challenge. Different extracts may contain distinct mixtures of metabolites, and similar biological outcomes may arise through different mechanisms. Consequently, a positive screening result should be interpreted as evidence of activity under specified conditions, not proof of a defined pharmacological mechanism. Chemical characterization and reproducibility are necessary to establish whether the observed activity can be attributed to identifiable constituents.

The investigation of mangrove-derived Streptomyces sp. MUM292 by Tan et al. (2018) illustrates the relevance of screening microbial extracts for antioxidant properties. Such findings can motivate additional research into inflammation-related effects, but the two endpoints remain distinct. Oxidative processes may contribute to inflammatory responses, yet an extract's antioxidant activity does not establish that it suppresses inflammatory signaling in living cells. Direct biological validation is therefore essential.

5.2 Antibacterial activity and the challenge of therapeutic selectivity

The antibiotic-resistance context described by Talebi et al. (2019) strengthens the need to investigate new antibacterial candidates. However, the discovery of an extract that inhibits bacterial growth is only an initial step toward addressing resistance. Researchers must determine its effective concentration, spectrum of activity, reproducibility, and potential toxicity to host cells.

The mechanistic perspective provided by Wei et al. (2015) is useful because it illustrates the importance of investigating how an antibacterial compound acts. However, its findings concern a compound from Porphyra haitanensis, not a Streptomyces-derived extract. Its relevance is therefore methodological rather than direct evidence of the activity of the extracts considered here.

A major trade-off concerns broad-spectrum activity versus

selectivity. An extract that affects multiple bacterial groups may offer practical advantages, but broad activity is not inherently beneficial if it also damages beneficial microorganisms or host tissues. Conversely, narrow-spectrum activity may be valuable where the target organism is clearly defined. The appropriate objective is therefore not simply to maximize inhibition, but to identify reproducible antibacterial effects with a favorable safety profile.

Further work should also distinguish activity against laboratory reference strains from activity against clinically or agriculturally relevant resistant isolates. Evidence from the former cannot automatically establish performance in the latter. Resistance-related claims require direct susceptibility testing and, where justified, mechanistic investigations.

5.3 Anti-inflammatory potential and the risk of misleading interpretation

The anti-inflammatory dimension presents a separate challenge because a reduction in a measured inflammatory marker can have several explanations. It may reflect a genuine change in inflammatory signaling, a reduction in cell number, interference with the measurement method, or generalized cellular dysfunction.

The antioxidant study by Tan et al. (2018) provides a reason to investigate relationships between oxidative activity and inflammation-related endpoints, but it does not resolve these possibilities. A rigorous investigation would therefore use independent endpoints and assess cellular viability alongside inflammatory responses.

The theoretical implication is that bioactivity should be interpreted as a pattern of related but distinguishable observations. If an extract reduces a selected inflammatory mediator while preserving cellular viability, the result may justify additional investigation. It would still not establish efficacy in an organism or patient. Such a conclusion would require evidence from more relevant biological models and, ultimately, appropriately designed translational studies.

Another consideration is the physiological function of inflammation. Inflammatory responses contribute to host defense and tissue repair, so indiscriminate suppression may be undesirable. The intended application must determine whether modulation of excessive inflammation, rather than generalized inhibition, is the relevant objective.

5.4 Immunostimulation: activation is not equivalent to protection

The immune-related references demonstrate why immunostimulation requires careful interpretation. Swain et al. (2007) examined nonspecific immune parameters in Labeo rohita and reported their seasonal variation. This illustrates that immune measurements can vary with environmental and physiological conditions, creating a need for controlled experimental comparisons.

Velázquez et al. (2017) investigated an interferon-gamma homologue in Nile tilapia and its association with immune responses under different stimuli. The study provides a rationale for examining defined immune pathways rather than relying exclusively on broad indicators of immune activation.

Wangkaghart et al. (2021) further considered immune responses alongside protective efficacy in a vaccine-adjuvant context. This distinction is especially important for evaluating bioactive extracts: measurable immune activation does not necessarily mean improved resistance to infection. The nature, duration, and functional consequences of the response must also be established.

These aquatic studies offer relevant methodological insights, but their findings should not be generalized automatically to mammalian systems or human therapeutics. Immune pathways, physiological conditions, and responses to biological agents may differ across species. The intended application must therefore guide model selection and endpoint interpretation.

5.5 Integrating the three activities and evaluating limitations

The principal contribution of the proposed framework is the separation of three activity domains before their integration. Antibacterial effects, inflammation-related changes, and immune stimulation should first be demonstrated independently. Only then can researchers determine whether a particular extract combines these properties at compatible concentrations.

This requirement is important because the activities may interact in unexpected ways. An extract might inhibit bacteria while also damaging host cells, reduce selected inflammatory markers while impairing normal immune function, or stimulate immune activity without producing a useful protective response. These possibilities are research questions, not established outcomes for the extracts considered in this paper.

The framework also has limitations. First, the supplied references do not directly test all three target activities in the same Streptomyces-derived preparation. Second, the

available evidence does not establish the chemical identity of a candidate extract with the proposed combined properties. Third, a literature-based synthesis cannot substitute for standardized laboratory experiments, independent replication, or toxicity assessment.

Future investigations should prioritize reproducible extraction, chemical fingerprinting, concentration-dependent biological assays, appropriate controls, and transparent reporting. Where promising activity is identified, additional research should investigate active constituents, possible mechanisms, stability, and application-specific safety. This staged strategy can reduce the risk of advancing candidates on the basis of isolated positive results.

6. Conclusion

Streptomyces-derived bioactive extracts represent a scientifically relevant area of natural-product research because of the chemical diversity associated with actinomycetes and the possibility of discovering compounds with useful biological properties. The supplied literature supports investigating these extracts within the broader context of antimicrobial resistance, secondary-metabolite diversity, oxidative activity, and immune regulation.

The analysis establishes that antibacterial activity, anti-inflammatory potential, and immunostimulation must be evaluated as separate but potentially complementary properties. Antibacterial inhibition does not independently demonstrate clinical usefulness; antioxidant activity does not prove anti-inflammatory efficacy; and immune activation does not necessarily indicate improved protection. These distinctions are essential for reliable interpretation.

The proposed framework integrates chemical characterization, antibacterial testing, inflammation-related assays, immune-function measurements, and preliminary safety evaluation. Its contribution is to establish a structured approach for investigating whether the three biological activities can coexist in a reproducible and biologically compatible preparation.

However, the present paper is a literature-based analysis and research proposal, not an experimental validation study. The available references do not establish that a particular Streptomyces extract has demonstrated all three activities simultaneously. Future laboratory investigations should address this evidence gap through standardized experiments, appropriate biological models, chemical analysis, and independent replication. Only after such evidence is obtained can the therapeutic or biotechnological value of specific extracts be assessed with confidence.

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