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Advancements in symbiotic phage interactions with microbial hosts: Bacteria, algae, and fungi.

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Introduction

The intricate relationships between bacteriophages (phages) and microbial hosts—bacteria, algae, and fungi—have long fascinated microbiologists. Traditionally viewed as parasitic entities, phages are now recognized for their potential symbiotic roles, influencing microbial ecology, evolution, and biotechnology. Recent advancements in genomics, metagenomics, and synthetic biology have illuminated the multifaceted dynamics of phage-host interactions, revealing their significance in environmental resilience, therapeutic innovation, and industrial applications [1].

Phages are the most abundant biological entities on Earth, with an estimated 10^{31} particles globally. While lytic phages destroy bacterial cells, lysogenic phages integrate into host genomes, forming prophages that can confer adaptive advantages. These include resistance to environmental stressors, enhanced metabolic capabilities, and defense against competing phages. Recent studies have shown that in contaminated soils, lysogenic phages carry auxiliary metabolic genes that help bacterial hosts detoxify heavy metals like chromium. This mutualistic relationship enhances bacterial survival and ecosystem stability. Moreover, phages facilitate horizontal gene transfer, promoting microbial diversity and evolution [2].

The surge in high-throughput sequencing, CRISPR-based phage-host mapping, and computational modeling has revolutionized our understanding of phage symbiosis. CRISPR arrays in bacterial genomes serve as historical records of phage encounters, enabling precise identification of host-phage linkages. Machine learning models now predict phage-host interactions based on genomic signatures, accelerating the discovery of therapeutic phages against antibiotic-resistant bacteria. Synthetic biology allows for the design of custom phages with enhanced specificity, stability, and payload delivery capabilities, opening avenues for phage therapy, microbiome engineering, and targeted gene editing. Algae, particularly cyanobacteria, are frequent hosts of cyanophages—viruses that infect photosynthetic microorganisms. Cyanophages play a pivotal role in regulating algal blooms, nutrient cycling, and carbon sequestration in aquatic ecosystems. Their ability to modulate algal population dynamics has implications for climate regulation and marine food webs [3].

Phage therapy is re-emerging as a promising alternative to antibiotics, especially against multidrug-resistant pathogens. Symbiotic phages that coexist with commensal bacteria offer a targeted approach that preserves beneficial microbiota while eliminating pathogens. In agriculture, phages are being used to control bacterial and fungal diseases in crops, reducing reliance on chemical pesticides. In aquaculture, cyanophages help manage algal blooms that threaten fish populations and water quality. Environmental applications include bioremediation, where phages enhance microbial degradation of pollutants, and climate mitigation, where cyanophage-algae dynamics influence carbon cycling. Genomic analyses have revealed that cyanophages often carry photosynthesis-related genes, such as psbA and psbD, which help maintain host photosynthetic activity during infection. This

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suggests a cooperative strategy where phages ensure host viability long enough to complete their replication cycle. Such interactions exemplify a form of symbiosis that balances viral propagation with host function. In biotechnology, cyanophages are being explored for biofuel production and wastewater treatment. By selectively targeting harmful algal species, phages offer a natural and sustainable method for managing water quality [4].

Compared to bacteria and algae, fungal-phage interactions—particularly involving mycoviruses—are less understood but increasingly recognized for their ecological and therapeutic relevance. Mycoviruses are often persistent and asymptomatic, residing within fungal hosts without causing lysis. Some confer beneficial traits, such as increased virulence in plant-pathogenic fungi or enhanced stress tolerance. One notable example is the mycovirus Cryphonectria hypovirus 1 (CHV1), which reduces the virulence of the chestnut blight fungus, offering a biocontrol strategy for forest conservation. Additionally, mycoviruses have been implicated in modulating fungal metabolism, sporulation, and secondary metabolite production, with potential applications in agriculture and pharmaceuticals. Advancements in RNA sequencing and fungal viromics are uncovering novel mycoviruses and their roles in fungal ecology. Despite these advancements, challenges remain. Phage-host specificity, evolutionary arms races, and regulatory hurdles complicate therapeutic deployment. These discoveries pave the way for engineered mycoviruses that could suppress pathogenic fungi or enhance beneficial ones in industrial fermentation processes [5].

Conclusion

Understanding the long-term ecological impacts of phage interventions is critical to avoid unintended consequences. Symbiotic phage interactions with bacteria, algae, and fungi represent a paradigm shift in microbiology. From ecological regulation to therapeutic innovation, phages are emerging as versatile allies in shaping microbial communities and addressing global challenges. Continued interdisciplinary research will unlock their full potential, transforming our approach to health, environment, and industry.

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