

assimilation, while a more stable intestinal microbiota helps suppress opportunistic pathogens and supports mucosal homeostasis. At the same time, probiotics stimulate antioxidant defenses and innate immune factors, thereby increasing the resilience of grass carp under intensive farming conditions. Beyond their direct effects on the host, probiotics also play an important regulatory role at the culture-system level. By reducing ammonia, nitrite, and other harmful metabolites, and by reshaping microbial communities in water, probiotics contribute to a healthier aquaculture environment that lowers physiological stress and disease pressure. This dual action on both fish and water makes probiotics especially valuable in healthy grass carp farming, where sustainable productivity depends not only on rapid growth but also on ecological stability, reduced antibiotic reliance, and improved survival. Therefore, probiotics should be regarded not merely as feed additives, but as multifunctional biological regulators that connect nutrition, immunity, environmental management, and green production.

Despite the encouraging progress, current research on probiotic application in grass carp still has several important limitations. First, many studies remain focused on short-term feeding trials and phenotypic observations, while the long-term effects on host health, ecological safety, and farming-system stability remain insufficiently clarified. Second, the responses of grass carp to probiotics are strongly influenced by strain specificity, dosage, developmental stage, feed composition, and environmental factors such as temperature, dissolved oxygen, and water quality. As a result, probiotic effects observed under laboratory or small-scale conditions are not always fully reproducible in commercial aquaculture settings. In addition, many candidate probiotics currently used in aquaculture are not host-associated strains, which may limit their colonization ability, stability, and functional consistency in the grass carp intestinal tract. Technological and industrial constraints also restrict broader application. The screening and functional verification of superior strains remain difficult, especially when safety, antagonistic activity, digestive contribution, immune regulation, and environmental adaptability must all be evaluated together. Standardized protocols for strain selection, product formulation, dosage control, storage stability, and delivery methods are still lacking. At the same time, large-scale production of highly active and stable probiotic products remains a challenge, particularly for formulations intended for diverse aquaculture environments. Regulatory uncertainty, biosafety assessment, and the need to prevent unintended ecological impacts further complicate practical deployment. These limitations indicate that the transition from experimental success to standardized and reliable field application is still incomplete.

Future development of probiotic-based green aquaculture technologies for grass carp will likely move toward greater precision, integration, and ecological orientation. One major trend is the selection of host-adapted and functionally targeted strains, especially those derived from the grass carp intestine or culture environment, because such strains are more likely to colonize effectively and perform consistently. At the same time, probiotic development will increasingly emphasize multi-strain formulations, synbiotic combinations, and coordinated use with feed management, water regulation, and ecological farming systems such as biofloc or low-exchange aquaculture. This systems-based approach is expected to improve not only fish growth and disease resistance but also nutrient recycling, microbial stability, and overall environmental performance of production systems. Another important trend is the use of omics-based technologies to uncover the precision regulation mechanisms of probiotics. Genomics, metagenomics, transcriptomics, and metabolomics can help identify functional strains, predict biosafety, reveal host-microbe interactions, and clarify how probiotics influence immunity, metabolism, and microbial network assembly in grass carp. These tools will support the development of next-generation probiotics, paraprobiotics, postbiotics, and even engineered microbial platforms with improved stability and targeted function. In the future, probiotic technology in grass carp aquaculture is likely to evolve from empirical supplementation toward data-guided microbial management. Such a transition will provide stronger support for antibiotic-free farming, environmentally friendly production, and the construction of resilient green aquaculture systems. In conclusion, probiotics have become an important foundation for promoting healthy, efficient, and sustainable grass carp aquaculture. Their future value will depend on whether research can move beyond broad efficacy claims toward standardized, mechanism-based, and field-validated application systems.