

feed conversion ratios and raised nitrogen and phosphorus utilization above 80%, transforming fish waste into additional biomass of finfish, shellfish, and vegetables. For marine grouper systems, floating treatment wetlands planted with halophytic species can simultaneously lower dissolved inorganic nitrogen and reduce CO₂ and N₂O emissions, providing co-benefits for water quality and greenhouse gas mitigation. Complementary measures include reformulation of feeds to reduce phosphorus content without compromising growth, optimization of stocking density to balance production and stress, and adoption of energy-efficient equipment to curb fuel and electricity use. Together, these green technologies and emission-reduction practices reposition grouper cage culture on a trajectory that aligns productivity with ecological resilience and climate goals. Maintaining suitable water quality in cage-cultured grouper requires aligning production intensity with ecological carrying capacity, supported by spatial planning and robust farm-level practices. Real-time monitoring and early warning systems enable rapid responses to environmental fluctuations and operational risks. Green technologies-ranging from IMTA and phytoremediation to low-phosphorus feeds and energy-efficient operations-substantially reduce nutrient emissions and greenhouse gas outputs, creating a more sustainable and resilient grouper aquaculture sector.

Acknowledgments

We would like to thank the anonymous reviewers for their detailed review of the draft. Their specific feedback helped us correct the logical loopholes in our arguments.

Conflict of Interest Disclosure

The authors affirm 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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